The Royal Aeronautical Society

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WILBUR WRIGHT MEMORIAL LECTURE AND CONVERSAZIONE

The Nineteenth Wilbur Wright Memorial Lecture was delivered before members of the Royal Aeronautical Society and a number of distinguished guests on Wednesday, September 16th, 1931, by Mr. Glenn L. Martin, F.R.Ae.S. (President of the Glenn L. Martin Company, of U.S.A.), in the Aeronautical Section of the Science Museum, South Kensington, London, S.W.7. The subject of the lecture was "The Development of Aircraft Manufacture."

The function was held at the Science Museum by kind permission of the Director, Colonel Sir Henry Lyons, Hon. D.Sc., F.R.S.

The Annual Dinner of the Council, preceding the Wilbur Wright Memorial Lecture, was held at the Museum. The President of the Society (Mr. C. R. Fairey, M.B.E., F.R.Ae.S.) was in the chair, and a number of distinguished guests were entertained. The following is a list of the Council and their guests who were present:—

Mr. C. R. Fairey, M.B.E., F.R.Ae.S., President of the Society (in the chair).

Colonel the Master of Sempill, A.F.C., F.R.Ae.S., Immediate Past-President.

GUESTS.

Mr. Glenn L. Martin, F.R.Ae.S., Wilbur Wright Memorial Lecturer.
His Excellency the Belgian Ambassador.
Colonel Sir Henry Lyons, Hon. D.Sc., F.R.S., Director of the Science Museum.
Air Vice-Marshal H. C. T. Dowding, C.B., C.M.G., Air Member for Supply and Research.
Sir Richard T. Glazebrook, K.C.B., F.R.S., F.R.Ae.S., Chairman of the Aeronautical Research Committee.
Sir Alan J. Cobham, K.B.E., A.F.C., Hon. F.R.Ae.S.
Dr. F. W. Lanchester, F.R.S., Hon. F.R.Ae.S.
Mr. R. J. Mitchell, Assoc.M.Inst.C.E., F.R.Ae.S. (Designer of the S.6.B.).
Professor A. G. Von Kármán, Aachen University.
Mr. G. Merton, M.C., M.A., Ph.D., F.R.A.S., Comp.R.Ae.S.I., Vice-Chairman, Air League of the British Empire.
Mr. J. D. Siddeley, C.B.E., F.R.Ae.S., Chairman of the Society of British Aircraft Constructors, Ltd.
Mr. Patrick Alexander, Hon. F.R.Ae.S.
Major B. F. S. Baden-Powell, Hon. F.R.Ae.S., Past-President, Royal Aeronautical Society.
Major M. F. Scanlon, American Military Attaché for Air.
Commander G. D. Murray, American Naval Attaché for Air.
Captain S. Takasu, Japanese Naval Attaché.
Herr A. H. Van Scherpenberg, Secretary of the German Embassy.
Major S. Andreas, Czechoslovakian Air Attaché.
Captain M. J. B. Davy, A.F.R.Ae.S.

VICE-PRESIDENTS.

Air Vice-Marshal Sir Vyell Vyvyan, K.C.B., D.S.O., Comp.R.Ae.S.I.
Lieut.-Colonel J. T. C. Moore-Brabazon, M.C., F.R.Ae.S., M.I.Ae.E.
Mr. H. E. Wimperis, C.B.E., F.R.Ae.S.
Professor L. Bairstow, C.B.E., F.R.S., F.R.Ae.S.
Mr. Griffith Brewer, F.R.Ae.S.

COUNCIL.

Captain P. D. Acland, Comp.R.Ae.S.I.
Major T. M. Barlow, M.Sc.(Eng.), F.R.Ae.S.
Major J. S. Buchanan, O.B.E., F.R.Ae.S., Deputy Director of Technical Development, Air Ministry.
Major G. P. Bulman, O.B.E., B.Sc., A.F.R.Ae.S.
Mr. A. H. Hall, C.B.E., A.F.R.Ae.S., Superintendent, Royal Aircraft Establishment.
Mr. J. E. Hodgson, Comp.R.Ae.S.I., Honorary Librarian, Royal Aeronautical Society.
Major D. H. Kennedy, O.B.E., F.R.Ae.S., Honorary Treasurer, Royal Aeronautical Society.
Captain A. G. Lamplugh, F.R.Ae.S., M.I.Ae.E.
Mr. M. Langley, Assoc.M.Inst.N.A., A.M.I.Ae.E.
Mr. W. O. Manning, F.R.Ae.S.
Lieut.-Colonel F. C. Shelmerdine, C.I.E., O.B.E., A.F.R.Ae.S., Director of Civil Aviation.
Mr. A. F. Sidgreaves, O.B.E., Comp.R.Ae.S.I.
Mr. Lawrence A. Wingfield, M.C., D.F.C., A.R.Ae.S.I., Honorary Solicitor, Royal Aeronautical Society.
Mr. R. McKinnon Wood, O.B.E., F.R.Ae.S.
Captain J. Laurence Pritchard, Hon. F.R.Ae.S. (Secretary of the Royal Aeronautical Society).

Immediately following the Council dinner and preceding the reading of the Wilbur Wright Memorial Lecture there was a reception by the President and Mr. Glenn L. Martin. During the evening, by kind permission of the Air Council, the band of H.M. Royal Air Force, conducted by Flight Lieut. R. P. O'Donnell, M.V.O., R.A.F., Captain, Royal Marines, Director of Music, Royal Air Force, played selections.

Among those who were present at the Conversazione and the Lecture were the following:—

Squadron Leader W. R. D. Acland, D.F.C., A.F.C., Colonel Aemelaeus-Aima, C.B.E., Madame Aemelaeus-Aima, Capt. E. S. Alcock, Mrs. Alcock, Flight Lieut. J. B. Allen, Mrs. Allen, Flight Lieut. J. H. Amers, M.B.E., R.A.F., Mrs. Amers, Mrs. Armneder, J. R. Ashwell-Cooke, Esq., Comp.R.Ae.S.I.

Miss E. Baker, F. Rodwell Banks, Esq., O.B.E., A.F.R.Ae.S., Capt. A. J. Barlow, Mrs. Barlow, M. O. S. Barrington, Esq., W. E. Bartels, Esq., F./O. P. F. M. Berkeley, G. T. Berry, Esq., H.H. Prince George Bibesco (President of the F.A.I.), W. J. Bilton, Esq., E. I. M. Bird, Esq., W. G. Bird, Esq., M.A., A.F.R.Ae.S., Mrs. Griffith Brewer, Cyril G. Brewer, Esq., W. Broadbent, Esq., F./O. G. S. Brown, A.M.I.Ae.E., H. M. Brutnell, Esq., H. V. Bulbrook, Esq., A.R.Ae.S.I., Mrs. Bulman, Squadron Leader C. G. Burge, O.B.E., A.R.Ae.S.I., — Burton, Esq., Mrs. Burton, Flight Lieut. J. Bussey, Group Captain H. R. Busteed, O.B.E., A.F.C., A.F.R.Ae.S.

Brig.-General W. B. Caddell, — Cansdale, Esq., Mrs. Cansdale, C. G. Carlisle, Esq., A.M.I.Ae.E., Mrs. Carlisle, Major B. C. Carter, F.R.Ae.S., Mrs. Carter, Wing Commander T. R. Cave-Browne-Cave, C.B.E., F.R.Ae.S., Air Commodore J. A. Chamier, C.B., C.M.G., D.S.O., O.B.E., A.F.R.Ae.S.,

Mrs. Chamier, J. Charnley, Esq., A.M.I.Ae.E., E. Chatterton, Esq., B.Sc.(Eng.), A.F.R.Ae.S., C. V. Coates, M.A., A.F.R.Ae.S., Lady Cobham, Squadron Leader S. N. Cole, A.F.R.Ae.S., W. S. Coleman, Esq., Stud.R.Ae.S.I., Lieut.-Commander C. N. Colson, R.N., A.R.Ae.S.I., Capt. J. B. L. Cordes, Miss G. Cottrell, Comp.R.Ae.S.I., H. Roxbee Cox, Esq., Ph.D., B.Sc., D.I.C., A.F.R.Ae.S., Mrs. Roxbee Cox, W. H. Craven, Esq.

H. Davies, Esq., B.A., A.F.R.Ae.S., Mrs. Davies, sen., Capt. Keith Davies, A.F.R.Ae.S., A. H. Davis, Esq., D.Sc., Mrs. Davis, B. Davitcho, Esq., Stud.R.Ae.S.I., Mrs. Davy, Mrs. George Digan, G. P. Douglas, Esq., M.C., D.Sc., Kathleen, Countess of Drogheda, C.B.E., Comp.R.Ae.S.I.

E. C. Gordon England, Esq., A.F.R.Ae.S., Mrs. Gordon England, Squadron Leader T. H. England, D.S.C., A.F.C., A.F.R.Ae.S., V. Ernst, Esq., B.Sc., A.F.R.Ae.S., Mrs. Ernst, O. Ernst, Esq., Colonel P. T. Etherton, H. B. Wyn Evans, Esq., M.B.E., A.F.R.Ae.S., Mrs. Wyn Evans.

A. Fage, Esq., A.R.C.Sc., F.R.Ae.S., Mrs. Fage, E. J. Fearn, Esq., B.Sc.(Eng.), A.F.R.Ae.S., N. A. Ferguson, Esq., A.M.I.Ae.E., Flight Lieut. Maxwell H. Findlay, D.S.C., D.F.C., Mrs. Findlay, A. H. G. Fokker, Esq., Miss I M. Forsyth, V. A. R. French, Esq., Stud.R.Ae.S.I.

H. H. Gardner, Esq., D. W. Genge, Esq., Mrs. Genge, Group Capt. N. J. Gill, C.B.E., M.C., H. R. Gillman, Esq., A.F.R.Ae.S., Mrs. Gillman, A. Gouge, Esq., B.Sc., F.R.Ae.S., Mrs. Gouge, C. G. Grey, Esq., Mrs. Grey, P. T. Griffith, Esq., A.F.R.Ae.S., H. Grinsted, Esq., O.B.E., B.Sc., A.F.R.Ae.S.

Lieut.-Colonel A. Hacking, D.S.O., M.C., Squadron Leader R. A. de Haga Haig, A.F.C., A.F.R.Ae.S., Mrs. de Haga Haig, Mrs. A. H. Hall, Mrs. J. Hall, J. Hardmann, Esq., R. St. Clair Harrison, Esq., Flight Lieut. J. A. G. Haslam, M.C., D.F.C., A.F.R.Ae.S., Mrs. Haslam, I. Hattori, Esq., Madame Hattori, R. M. Hayes, Esq., Stud.R.Ae.S.I., A. W. Higson, Esq., Mrs. Higson, T. W. Hill, Esq., J. L. Hodgson, Esq., B.Sc., A.F.R.Ae.S., Mrs. J. L. Hodgson, Miss C. Holt, S. G. Hooker, Esq., Stud.R.Ae.S.I., C. Stuart Humphreys, Esq., A.R.Ae.S.I.

C. H. Jackson, Esq., Stud.R.Ae.S.I., F./O. V. B. J. Jackson, Thurstan James, Esq., Miss F. Jarvis, Miss Amy Johnson, C.B.E., A.R.Ae.S.I., G. Lewis Jones, Esq., R. G. Jones, Esq., Stud.R.Ae.S.I.

Morley Kennerley, Esq., W. L. Kilcoin, Esq., T. D. Kumar, Esq., Stud.R.Ae.S.I.

Dr. G. V. Lachmann, A.F.R.Ae.S., Mrs. Lamplugh, Mrs. F. W. Lanchester, H. V. Lanchester, Esq., F.R.I.B.A., Mrs. H. V. Lanchester, Mrs. M. Langley, R. Langley, Esq., Cav. E. Lanzerotti-Spina, A.F.R.Ae.S., Mrs. Lanzerotti-Spina, A. F. de Ledesma, Esq., Comp.R.Ae.S.I., Major G. Lees, O.B.E., A.R.C.S., M. Lewin, Esq., A.F.R.Ae.S., Mrs. Lewin, David Lightfoot, Esq., D. Lister, Esq., B.Sc., A.F.R.Ae.S., T. A. S. Lloyd, Esq., Comp.R.Ae.S.I., Mrs. Lloyd, G. Lyon, Esq., M.Sc., A.F.R.Ae.S.

Mrs. MacGinty, Commander L. D. Mackintosh, D.S.C., A.F.R.Ae.S., R.N., Mrs. Mackintosh, Sir Robert McLean, Mrs. Martin, sen., R. W. Mason, Esq., Colonel J. S. Matthew, C.M.G., D.S.O., R. Borlase Matthews, Esq., Wh.Ex., F.R.Ae.S., Mrs. Borlase Matthews, Major R. H. Mayo, O.B.E., F.R.Ae.S., Mrs. Mayo, F. W. Meredith, Esq., Mrs. Merton, H. H. Morris, Esq., Comp.R.Ae.S.I., Mrs. Morris, J. T. Morton, Esq., A.F.R.Ae.S.

N. H. Nash, Esq., Stud.R.Ae.S.I., F. B. Nathan, Esq., Mrs. Nathan, Miss S. Nathan, Commander G. I. Niculescu (Royal Rumanian Navy), Y. Nitta, Esq., Madame Nitta, Miss Nobbs, Squadron Leader F. A. Norton, M.Sc. (Cantab.), M.I.Ae.E.

Capt. G. P. Olley, Mrs. Olley, Commander Ralph Ostie, J. S. L. Oswald, Esq., B.Sc., A.F.R.Ae.S.

F. Handley Page, Esq., C.B.E., F.R.Ae.S., Mrs. Handley Page, J. Paine, Esq., Mrs. Paine, W. A. H. Paine, Esq., Stud.R.Ae.S.I., Wing Comdr. R. G.

Parry, D.S.O., R.A.F., A.F.R.Ae.S., R. C. Passmore, Esq., N. A. V. Piercy, Esq., D.Sc., F.R.Ae.S., Mrs. Piercy, R. K. Pierson, Esq., M.B.E., B.Sc., F.R.Ae.S., C. A. Pike, Esq., A.F.R.Ae.S., Mrs. Pike, F. Pilling, Esq., A.F.R.Ae.S., Mrs. Pilling, E. H. Pledger, Esq., J. Pontremoli, Esq., Flight Lieut. R. C. Preston, A.F.C., A.R.Ae.S.I., Mrs. Preston, Mrs. Laurence Pritchard, Squadron Leader H. M. Probyn, D.S.O., Capt. C. A. Puga, E. G. Pyne, Esq.

Dr. J. Rannie, Mrs. Rannie, Mrs. H. Rawlinson, S. C. Redshaw, Esq., M.Sc., A.F.R.Ae.S., C. H. Roberts, Esq., A.I.A.E., F.I.M.T., E. W. Roberts, Esq., H. S. Robertson, Esq., Major T. E. Robertson, O.B.E., A.F.R.Ae.S., Mrs. Robertson, C. G. Rogers, Esq., A.R.Ae.S.I., W. S. Rope, Esq., A.F.C., M.A., A.F.R.Ae.S.

R. Saunders, Esq., W. P. Savage, Esq., A.F.R.Ae.S., Madame Van Scherpenberg, Herr F. N. Scheubel (Aachen), S. Scott-Hall, Esq., M.Sc., D.I.C., A.F.R.Ae.S., the Hon. Mrs. Forbes-Sempill, Commander L. C. Sharman, Comp.R.Ae.S.I., R.N., Mrs. Sharman, Mrs. Shelmerdine, M. M. Singh, Esq., M. L. Sodhi, Esq., Stud.R.Ae.S.I., A. M. H. Solomon, Esq., Harold Solomon, Esq., Professor R. V. Southwell, M.A., F.R.S., F.R.Ae.S., Miss M. Steet, H. J. Stieger, Esq., D.I.C., A.F.R.Ae.S., Mrs. Stieger, Capt. R. H. Stocken, A.M.I.Ae.E., A. J. Stubbings, Esq., Capt. J. Summers, J. Suthering, Esq., A.R.Ae.S.I.

W. A. Tamblin, Esq., A.F.R.Ae.S., Oliver Thornycroft, Esq., O.B.E., A.F.R.Ae.S., Mrs. Thornycroft, H. C. H. Townend, Esq., B.Sc.(Eng.), A.F.R.Ae.S., Miss D. Travers, Flight Lieut. G. W. Tuttle, Baron de Tuyll.

Sir A. Verdon-Roe, O.B.E., F.R.Ae.S., M.I.Ae.E., Miss A. Verdon-Roe, E. Verdon-Roe, Esq., Miss B. Voyce.

J. L. R. Waplington, Esq., Mrs. Waplington, Capt. C. E. Ward, Mrs. Ward, Miss E. M. Webb, Comp.R.Ae.S.I., Noel Whiteside, Esq., Herr C. Wieselberger (Aachen), E. Wieser, Esq., B.Sc., D.I.C., Stud. R.Ae.S.I., D. L. Hollis Williams, Esq., B.Sc., A.F.R.Ae.S., Mrs. Hollis Williams, Colin Williamson, Esq., C.B.E., F.R.P.S., R. P. Wilson, Esq., C.B.E., Mrs. Wimperis, Miss B. Wimperis, Miss E. Wimperis, Mrs. Wingfield, C. G. H. W. Winter, Esq., Mrs. Winter, H. T. Winter, Esq., Founder Member R.Ae.S.I., Miss Florence M. Wood, Mrs. McKinnon Wood, Professor R. W. Wood, F.R.S., Miss M. Wykes.

H. M. Yeatman, Esq., B.A., A.F.R.Ae.S., Mrs. Yeatman.

Mr. C. R. Fairey, M.B.E., F.R.Ae.S., President of the Royal Aeronautical Society: Before he introduced the reader of the Wilbur Wright Memorial Lecture for 1931, it was his pleasant duty to present certain awards that have been made by the Council for the year 1930-31.

The highest honour of all was the Society's Gold Medal, which had been awarded only five times since its inauguration in 1909. It was an honour which was very jealously guarded indeed, and although on this occasion it was not awarded, it was pleasing to recall that the first recipients were the Wright brothers. The others were Professor Chanute, Professor Bryan with Mr. E. T. Busk, Dr. Lanchester and Professor Prandtl. The international character of the Society's work was illustrated by the fact that, of the recipients of the Society's Gold Medal, three were American, three were English, and the last was of German nationality.

The Society had two other Gold Medals at its disposal—the Simms and the Taylor Gold Medals. The Simms Gold Medal was awarded for the best paper in any year, read before the Society, on any science allied to aeronautics—for example, meteorology, wireless telegraphy, instruments, etc. It was open to members and non-members. This year the Council had awarded the Simms Gold Medal to Dr. A. H. Davis for his very valuable paper on "Noise." Dr.

Davis was Senior Assistant in the Physics Department of the National Physical Laboratory, and was in charge of the Sound Division, which was formed in 1922. Anyone who had read Dr. Davis's paper would agree that the award of the Simms Gold Medal in respect of it was most fitting.

The Taylor Gold Medal was awarded for the most valuable paper submitted or read during the previous Session before the Society by either a member or non-member. This year the Council had awarded the medal to Squadron Leader W. R. D. Acland, for his paper on " Deck Flying," which paper had created so much interest. Squadron Leader Acland, who was on the staff of the Director of Operations and Intelligence at the Air Ministry, had been engaged almost continually in flying with the fleet, and had carried out some of the earliest experiments in deck landing at the Isle of Grain.

The next award was the Silver Medal of the Society, which was awarded, in respect of some definite advance in aeronautical design, to either a member or non-member. It was not an annual award, but was presented only when some special work had been carried out. This year it had been awarded to Mr. H. C. H. Townend, for his work in connection with the well-known Townend Ring. Mr. Townend was an Assistant in the Aerodynamics Department of the National Physical Laboratory, and now became one of the band of famous engineers who had received the medal. The last occasion on which it had been presented was in 1929, the recipient on that occasion being Sir Frederick H. Royce.

The R.38 Memorial Prize, which was founded in 1923, was awarded for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers relating to airships. It was considered to be the most important prize which could be awarded for a paper dealing with the airship problem, and had been won in the past by, among others, the late Major G. H. Scott, the late Colonel V. C. Richmond, and Commander J. C. Hunsaker. Of the papers received this year, two were of such merit that it was difficult to judge between them, and the Council had decided to divide the prize between the authors of two papers—one paper by Miss L. Chitty and Professor R. V. Southwell on " Some Problems of Primary Stress Determination in Airship Hulls," and one by Mr. W. G. Bird on " The Influence of Atmospheric Humidity and other Factors upon the Static Lift of Airships." Professor Southwell occupied the Chair of Engineering at Oxford University. He had been at one time in charge of design of non-rigid airships, had been Superintendent of the Aerodynamics Department of the National Physical Laboratory, and in charge of experimental work at the Royal Aircraft Establishment. Miss Chitty was one of the few lady Associate Fellows of the Society. She had served during the War in the Air Ministry, being responsible for the strength of aircraft, and for some years since had been working with Professor Southwell on airship and allied problems. Mr. Bird had been Research Engineer under the Airship Guarantee Company, the builders of R.100, and, until recently, was assistant engineer in charge of aircraft instrument research at the works of Messrs. S. Smith and Sons (M.A.), Ltd., Cricklewood.

Another prize was the Busk Memorial Prize, founded in memory of Edward T. Busk, who had lost his life in 1914 while carrying out full-scale experiments, which had proved of the greatest possible value in obtaining a stable aeroplane. The prize this year had been awarded to Mr. A. Gouge (General Manager and Chief Designer to Messrs. Short Brothers, Ltd.), for his paper on " Some Aspects of the Design and Construction of Sea-going Aircraft."

Lastly, there was the Pilcher Memorial Prize, founded in memory of Percy Pilcher. It was awarded to a student of the Society for the best paper on any subject dealing with aeroplanes, and this year it was to be presented to Mr. S. G. Hooker, for his paper on " The Compressibility Effects in High-Speed

Air Flow." Mr. Hooker was an assistant in the Aerodynamics Department of the Imperial College of Science and Technology, South Kensington.

There is one final award to be made at this meeting, not an award of the Society, but one which was a very high honour indeed. He referred to the Daniel Guggenheim Gold Medal for 1931, which had been awarded to Dr. F. W. Lanchester. Before calling upon Mr. Griffith Brewer, a Vice-President of the Society and the representative of the Guggenheim Medal Award Board in this country, to make the presentation, he took the opportunity, on behalf of the Society, very earnestly to thank the promoters of the Guggenheim Fund for all they had done in the past for the Society. By their financial aid they had done a very great work in the world, and it was very greatly appreciated. The Society wished to record permanently its appreciation of the valuable help it had received, and was sending a memorial, on vellum, to Mr. Harry Guggenheim. This had been signed by the Society's two Royal Patrons—H.R.H. the Prince of Wales and H.R.H. the Duke of York—and by other officers of the Society.

The President then invited Mr. Griffith Brewer to present the Guggenheim Memorial Medal to Dr. Lanchester.

Mr. GRIFFITH BREWER, Vice-President, Royal Aeronautical Society: It was a privilege to him, as the English representative of the Daniel Guggenheim Memorial Fund, to present the medal to Dr. Lanchester. This was the first occasion on which it had been awarded to an Englishman; it had been awarded only twice previously, the two earlier recipients being Mr. Orville Wright in 1929 for the invention of the aeroplane and Dr. Prandtl in 1930 for his pioneer work in the theory of aerodynamics. The medal had been awarded to Dr. Lanchester for his contributions to the fundamental theory of aerodynamics. Many people had not heard of his experiments, which were carried out twenty years ago; some others had only recently recognised their great importance, but the Royal Aeronautical Society had recognised it earlier, for in the year 1926 it had invited Dr. Lanchester to deliver the Wilbur Wright Memorial Lecture, on the subject of his experiments. The Daniel Guggenheim Gold Medal is only awarded for a notable achievement in the advancement of aeronautics, and its award on this occasion to Dr. Lanchester was evidence of recognition, in the highest aeronautical quarters in America, of the value of the work which he had performed. It was of interest to note that all three recipients of the Daniel Guggenheim Gold Medal had also received the Gold Medal of the Royal Aeronautical Society; the latter medal was presented to Mr. Orville Wright in 1909 and to Dr. Prandtl in 1927. In conclusion, Mr. Griffith Brewer said he felt sure that the Members of Council and indeed the whole membership of the Royal Aeronautical Society would congratulate Dr. Lanchester upon the receipt of the Daniel Guggenheim Gold Medal as marking the recognition in America of the value of his work.

Dr. F. W. LANCHESTER: He confessed that he was rather overwhelmed by the beauty of the Daniel Guggenheim Gold Medal, so much so that some of the ideas he had had in his mind, and which he had intended to convey to the meeting, had faded somewhat. However, during the evening he had been reflecting upon the resemblance in some respects between scientific discovery and scientific work, on the one hand, and wine, on the other hand. He was not suggesting that scientific discovery and scientific work went to one's head necessarily, though probably they did sometimes. What he did suggest was that there seemed to be something equivalent to a " vintage " in scientific discovery and scientific work. When a new wine was produced, some of the experts whose duty it was to taste new wine would perhaps pronounce that it was a good wine, whereas usually the public would not regard it as being fit for consumption at that stage. Perhaps scientific work was in a somewhat similar position. It had occurred to him that the work of Faraday was an example of a wonderful vintage, so good that the ordinary man could appreciate it, whereas his (Dr. Lanchester's)

was one of those vintages which the ordinary man, when he first tasted it, would not think much of; it was such that twenty years had to elapse in order that it should be appreciated as a reasonably good vintage. He expressed his gratitude to their American cousins for having presented to him, as a token of appreciation, so wonderfully fine a work of art, and one which he assured them he would always value very highly.

His earlier work was appreciated in this country mainly because of the developments which the Brothers Wright had effected in America. The publication of his book on "Aero Flight" had called for a great effort on the part of the publisher; he (Dr. Lanchester) had had to take part in the gamble, and he believed that he would have been very much out of pocket but for the fact that at about that time, or shortly before, the Brothers Wright had been carrying out some wonderful pioneer work in the United States and had thereby concentrated the attention of everyone upon aeronautics. Probably, due to that work, his book had been accorded a reception which otherwise would have been impossible. Therefore, he was doubly indebted to America—for the appreciation resulting from the work of the Brothers Wright, and for the further appreciation through the medium of the Daniel Guggenheim Gold Medal.

The PRESIDENT: Before inviting Mr. Glenn L. Martin to deliver the nineteenth Wilbur Wright Memorial Lecture, he would remind his audience that the memorial lecture was founded in 1913 to perpetuate the memory of that great pioneer, Wilbur Wright, who, in association with his brother, Orville Wright, had constructed and flown the first man-carrying aeroplane, beneath which those who were to hear the nineteenth lecture were assembled. The first of the series of memorial lectures was delivered by Sir Horace Darwin in 1913, and subsequent ones by such distinguished lecturers as Sir Richard Glazebrook, Professor Bryan, Professor Bairstow, Commander Hunsaker, Rear-Admiral Taylor, Dr. Lanchester, Mr. Handley Page, the Hon. William P. MacCracken, jun., and Mr. Ricardo.

The Royal Aeronautical Society was justly proud of the fact that it was by far the oldest aeronautical society in the world, having enjoyed, or at least endured, more than sixty-five years' continuous existence, having lived through periods of very great discouragement, but during which the art or science which it was founded to encourage had advanced at a pace which had staggered humanity. That advance had culminated during the past year in the breaking of most of the world's important records, and it gave promise of future advancement even more rapid than had been achieved during the past decade. The Society had been a meeting place and a source of encouragement for those pioneers who had seen the future with a much truer vision than had the many millions of sceptics. It had followed that at some stage in man's quest of the true principle of flight the point would be reached at which one could leave the earth's surface in an apparatus lifted by its own power, and under control, and beyond doubt or question the first genuine flight was made by the Wright Brothers on December 17th, 1903.

Throughout its existence the Society had always maintained a very high standard in its lectures, and the Wilbur Wright Memorial Lecture was the culminating lecture of the session. It was the usual practice for the lecture to be delivered each year on a suitable date in May, as near the anniversary of the death of Wilbur Wright as possible. This year, however, in consultation with Mr. Orville Wright and Mr. Griffith Brewer, a trustee of the fund, it had been agreed to postpone the lecture to a later date in order that it could be delivered by so distinguished an authority as Mr. Glenn L. Martin. Mr. Martin was one of the real pioneers of American aviation, who was actively engaged in it only a few years after the historic flight of the Wright Brothers. He had designed and built a machine, and had taught himself to fly on it. He had continued to fly regularly, and had become one of the leading constructors of every type of

aircraft in the United States. He had the F.A.I. Aviation Certificate, dated 10th October, 1911, and had qualified for the F.A.I. Expert Aviator's Certificate No. 2 in October, 1912. For some years he had been associated with the Wright Brothers, and in 1917 had organised the Glenn L. Martin Company, when he had designed the Martin "bomber," which had brought him into great prominence. In every way he was well fitted to join the distinguished band of Wilbur Wright Memorial lecturers.

Mr. GLENN L. MARTIN then delivered his lecture.

THE DEVELOPMENT OF AIRCRAFT MANUFACTURE

BY

GLENN L. MARTIN, *Fellow of the Society*

Even from the early days of 1860, when your countryman Wenham experimented with gliders, the development of aerodynamics has been a systematic search for facts. The well-directed efforts of Wilbur and Orville Wright to search out the fundamentals of flight gave a profound impetus to contemporary and later experimenting, and libraries have been filled with the orderly research of aeronautical science. The development of manufacturing practice, however, has been dictated by the immediate needs of the moment, largely without the benefit of methodical study.

I trust I shall not be suspected of pleading a case either for the art of manufacturing, or for aeronautical science, as in the early days it was not unusual for me to find myself designing with one hand, while, in a manner of speaking, manufacturing with the other.

It is becoming increasingly evident that systematic study of aircraft manufacturing is of fundamental importance. We are not yet, it seems, able to place our goods upon the market in the correct form and at the correct price to attract public patronage. It seems to me that improvement is essential in the methods of producing aircraft, not primarily that we may out-do each other, but rather, that aeronautics as a whole may attain a better economic position.

Unquestionably the problem is a difficult one. Improvement of quality with reduction of price, we are told, wait upon volume of business, and volume is to be forthcoming, with better quality at lower price, presenting an apparent stalemate.

"How," inquires the works manager, "can standardisation and facility for reproduction be achieved, when designs are constantly changing?"

And it is true that within fifteen years designs and materials have changed radically and completely. The designer, observing his professional brothers engaged in continuous improvement of automobiles, railways and boats, feels that the improvement of aircraft is still far from complete. And this feeling is confirmed by the substantial fact that, throughout the world less than 4,000 commercial airplanes have been sold to users in the last twelve months.

A moratorium in design would permit standardisation of manufacture and perhaps increase sales. It would assuredly facilitate planning, and planning, we realise, is the foundation of good manufacturing. Granting the premise we realise the impossibility of such an arrangement.

Airplanes were not manufactured, in the modern sense of the term, until the war. The great concentration of effort applied then was directed almost entirely toward wood construction, only fittings being worked out in metal.

In 1922, when metal first began to be extensively used, it was not fully realised that the philosophy of manufacturing, if I may call it that, was to undergo a profound change. If recollection serves, one's attention was more urgently

occupied with the difficulties that arose in the troublesome process of converting shop practices from wood to metal. Before long, however, we began to sense something of the far-reaching importance of the move. It so happened that our first orders of more than 100 of a given type of plane were received not long after the adoption of metal construction, and we began thinking seriously of the future problem of constructing airplanes with studied efficiency in manufacturing.

It seemed obvious that there should exist certain fundamentals in the science of manufacturing, and a systematic research was inaugurated to define them.

FIG. 1.

Air view of the Glenn L. Martin Company's plant 10 miles east of Baltimore, Maryland, located in the north-west corner on a tract of 1,243 acres, paralleling the main line of the Pennsylvania Railroad for 1½ miles and embracing five miles of water front. The floor space is 300,000 square feet.

I would like to explain that even at that earlier date we realised we would ultimately be required to abandon the factory and location which we then occupied in Cleveland, Ohio, and it was proposed to plan, in so far as possible, for an ideal plant which would embody all the lessons learned from years gone by, and which could successfully cope with all conditions that might arise for many years to come.

The search eventually disclosed quite clearly that there existed a multitude of specific requirements for successful aircraft manufacture, some applicable to certain plants and types of aircraft, some requisite for others, frequently with wide variation in the various cases.

To clarify this rather confusing situation classification was made of a series of factories, both real and fictitious, so selected that they would completely cover all types of aircraft. The fictitious factories included establishments that might be producing large quantities of aircraft at some future day, and others that might be producing types of aircraft not yet fully conceived. Some of the test cases were laid in densely-populated cities, and others in small towns. After including all the possibilities in such fashion, the results were charted and an attempt made

to visualise the problem in its future, as well as present, aspects. When the study charts of all the elements were completed, we selected only those which had the most universal application, and did not give much value to those factors which appeared to be temporary or local.

It was suprising to find that the truly fundamental requirements for an ideal aircraft manufacturing establishment are few, consisting only of the suitability of the material used, the capability to swing from one type of construction to another, efficient plant layout, an adequate system of planning, the working conditions of personnel, and lastly, a suitable organisation. While adequate

FIG. 2.

Employees' parking space. This parking space is hard surfaced and will accommodate 1,000 *automobiles. In the foreground is building for storage of oils, dope and paints which is kept heated by steam and uniform temperature maintained at all times. The foundation of this building serves as a clear water reservoir for fire protection. The building in the background is the switch house, where power from transmission lines is reduced from* 13,800 *volts to* 440 *volts for use in operating factory equipment.*

financing is manifestly a primary requirement, it was not considered to be a need peculiar to the manufacturing of aircraft, and so obviously a necessity as scarcely to require mention.

Having isolated the really important factors, we set about the task of studying each in somewhat greater detail.

Concerning the major material to be used, it is clear that the type and arrangement of all machinery and appliances is governed quite largely by the major materials used in construction. It will readily be appreciated that frequent changes in the principal materials employed involve harmful inefficiencies, both direct and indirect, and it appeared to us that the determination of a material for permanent use could be based upon suitability in accordance with the following specifications:—

1. Strength-weight characteristics.
2. Shock-endurance qualities.
3. Suitability for machining and forming.
4. Adaptability for permanent fastenings.

5. Reaction to moisture, exposure and temperature.
6. Defects and uniformity.
7. Cost.
8. Source of supply and delivery.
9. Ease of inspection.

As an example, it will be seen that wood fails to adequately satisfy several of the above conditions. It has the characteristic of changing dimensions with moisture content and it is subject to a wide variety of defects, some of which are not easily detected. This point is mentioned in passing as it is typical of materials

FIG. 3.

Section of tool department. This unit is devoted entirely to the manufacture of special tools and jigs, necessary for the fabricating of airplane parts. Large machine in background is a 14-foot Gray planer used for making dies and other heavy tools for forming in brakes.

which cannot be used successfully due to the fatal interruptions which they cause in the vital flow of parts to the assembly line. Further exposition will be given on this topic a little later on.

The comparative suitability of various materials for successful manufacturing of aircraft may be quite easily determined by analysis according to the characteristics just outlined. It is not necessary to follow any rigid system of testing. Strength-weight ratios, and shock-endurance may be determined by any of the usual laboratory methods. Suitability for machining and forming includes drilling, turning, milling, machine and hand bending, bumping, and similar shop operations. The amount of deformation sustained without cracking is important. As Taylor has pointed out many years ago, the speed of machining and tool cost should not be overlooked. Ease of heat treatment should be considered.

A word may be said about suitability for fastenings. Aircraft of all types contain a multitude of joints. The facility for making reliable joints is clearly of great importance for manufacturing. Joints in wood may be readily made, but are of questionable durability. Manufacturing methods have been developed for

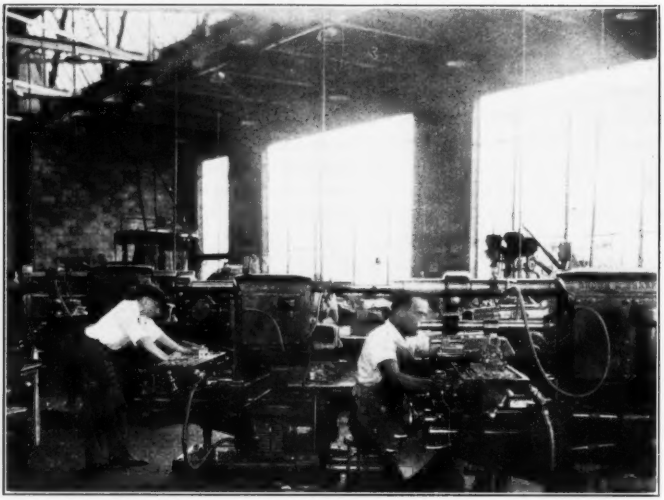

FIG. 4.

Section of tool room—milling machines.

FIG. 5.

Section of tool room—planers.

FIG. 6.

Section of sheet metal machine shop showing battery of punch presses in operation with brakes and other sheet metal working equipment in background.

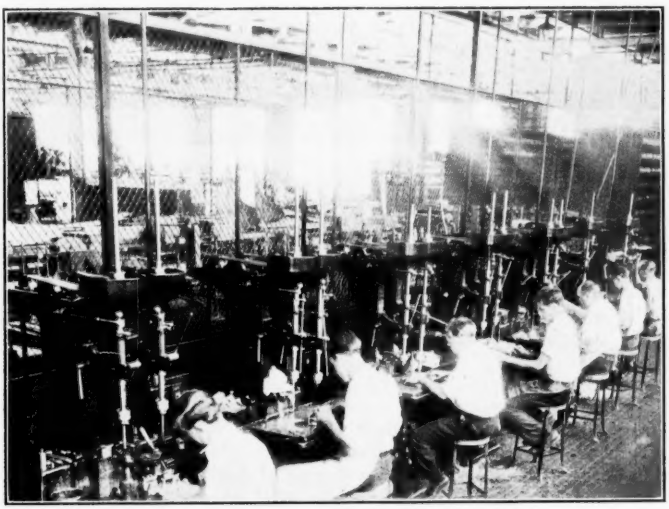

FIG. 7.

Section of machine shop—gang drills.

making joints in metal by welding, riveting, bolting, soldering, or by mechanical locking devices. Tests should be designed to show the comparative time required to make joints and the structural integrity of the joints when completed, with due allowance for the effects of age, shock and possible deterioration. Investigations of this character may be highly productive of beneficial results.

The effects of moisture and exposure may cause endless difficulty in manufacturing. For example, a material which is liable to serious corrosion requires elaborate precautionary measures for its protection, and these necessary operations may profoundly affect fabrication.

The importance of defects and uniformity should be obvious, and yet untold nuisance has resulted from procrastination in the use of such materials. Happily we now have ready access to many materials which do not have an inherently high percentage of defects.

Source of supply comes naturally to mind when speaking of the defects of materials. Experience has repeatedly proven the low cost of using high quality

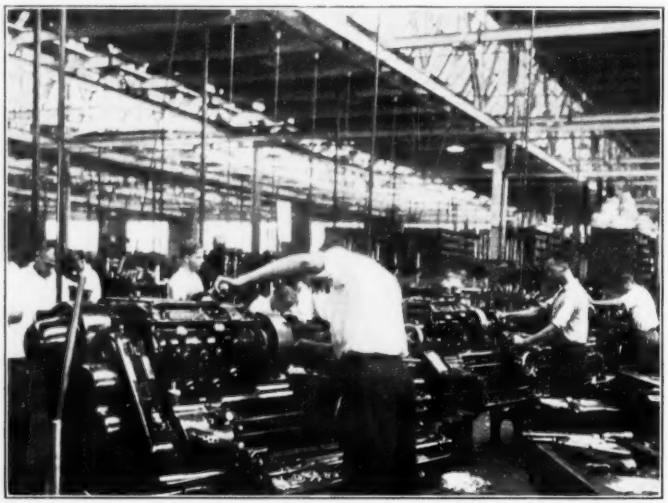

FIG. 8.

Section of machine shop—engine lathes.

materials. Source and delivery are very important in the manufacture of military aircraft, with its possibilities of sudden and drastic expansion in case of war. The same principles apply to commercial manufacture. Some thought must be given to the embarrassment that results if a successful sales programme is handicapped in inability to supply a willing market due to laggard delivery of material.

Ease of inspection should be taken into account when considering materials. Frequent occasions arise when it is necessary to investigate important assemblies to dispel all doubt as to their suitability for use, and it would appear that there is a definite gain in using materials that are readily susceptible to conclusive inspection, and thus avoiding the replacement of doubtful parts.

The selection of duralumin and carbon steel as major materials for aircraft construction came about by trial and error rather than by selective analysis, and I think that when congratulating ourselves upon having finally at our command materials that lend themselves to efficient manufacturing methods, we should also

bear in mind that a great deal of distress can be avoided in the future if we will measure materials against requirements before adopting them. To demonstrate the point, I will, with your indulgence, relate a little story which happened some years ago. We had been building seaplane floats of two-ply mahogany planking in the manner current at the time. We had built some of duralumin but had been somewhat alarmed at the rapid corrosion which took place in the early grades of that metal, and the protective methods now used had not been perfected. Nevertheless, the water soakage of the wood was annoying and we searched for something better, finding it at last, as we felt sure, in a material known as "rubber board," consisting of hard-cured globulated rubber pressed in sheets between rubber-impregnated fabric faces. This material would not soak up water, it would not corrode, warp, shrink nor deteriorate. It seemed to have good stiffness and shock-resisting properties. In our enthusiasm we immediately

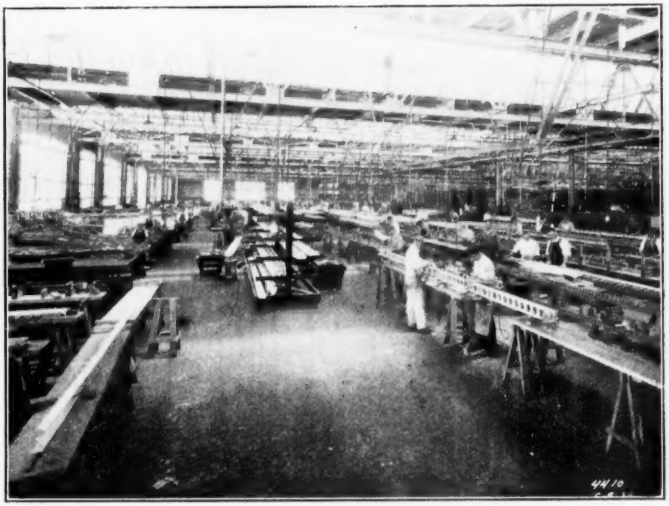

FIG. 9.

View of section of wing rib department. In this department all wing ribs, wing spars and assemblies of wing frames are completed. In the right foreground is the wing spar assembly and in the left foreground is the wing rib assembly. These are riveted assemblies, the pieces being laid in special forms or jigs to prevent distortion of the metal due to riveting.

adopted it for a production quantity of floats, applying it to decks, bottoms and internal bulkheads. A few months of service proved to us that this material had two serious defects. By continued submersion in warm sea water it had a slight, but positive tendency to soften. Under severe local loads the material did not hold its fastenings securely. As a result of the slight softening the high landing and take-off pressures deformed the bottom plating, and the localisation of water forces caused by these deformations threw highly concentrated loads upon certain screw fastenings, and bottoms began to fail. Shortly afterwards we replaced all bottoms with mahogany planking. The decks and bulkheads meanwhile were giving excellent service, and continued to do so during the several years that the airplanes remained in service. This incident further impressed us with the great importance of material studies.

While the selections of carbon steel and duralumin were made without deliberately systematic analysis, still, such an analysis has been very useful in determining the probable permanence of these materials for future use in the aircraft programme. By this means one can become assured that these two materials will be efficiently useful for a time long enough to warrant extensive planning with them as a basis.

Now, as to the form in which the metals are to be used. This simple question introduces a most far-reaching train of thought having fundamental effects upon design, space requirements, floor plan layout and choice of equipment. Duralumin for example, can be obtained in sheet, or in the form of tubing, and various sectional shapes such as angles, channels, etc. It can also be obtained in the extruded form. The cost of the raw material as it comes to the aircraft manufacturer and the delivery of the material are different in each of the different cases. Fortunately, however, the facts in each case are quite readily available, and it

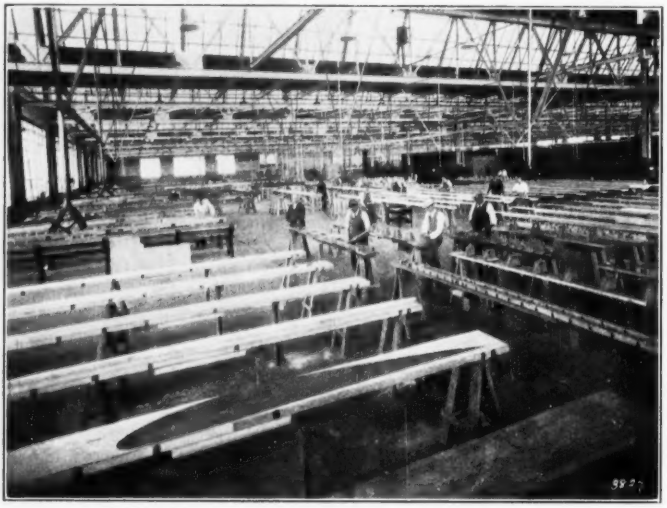

FIG. 10.

Section of wing department. This view shows specialised tool and cabinet makers setting up special fixtures for assembly of wing spars and other units.

is possible to compare the different forms of material in accordance with the characteristics of suitability which I have already enumerated. As in all such problems, some personal judgment must be exercised and some prediction of future conditions must be made.

From experience of previous years we knew that delays in assembly processes were very costly. It is also apparent that continual changes in design and construction could be expected for some years to come, due to the continued progress in aircraft development, and from these two considerations it appeared to be unusually important that one should be in a position to incorporate any necessary changes in current construction without waiting for new supplies of material. On the other hand, it is not desirable to carry a large and expensive inventory of raw material, as would be necessary if one wishes to stock all necessary sizes of structural shapes and tubing. Comparative studies were made to show the

amount of inventory which should be carried to avoid delays, and it was clearly shown that if sheet was carried in stock, and shapes made in the factory as needed, the saving would be sufficient to pay for the necessary machinery and leave a comfortable margin, inasmuch as the cost of sheet is materially less than rolled or extruded shapes. Furthermore, stocks of sheet unused at one time may be readily employed a little later on in other designs, while shapes and tubing are not nearly so universal in application.

We accordingly decided to use duralumin in sheet form, and this decision was further reinforced by the fact that the strength-weight ratio of sheet material is somewhat higher than extruded duralumin.

This decision was reached in 1927 and we immediately procured a special 200-ton press of 14ft. length, together with a shear of the same length for cutting strips from which sections could be made in the press. A 500-ton, 18ft. unit and a complete line of accessory equipment has since been added. I might explain

FIG. 11.

Section of wing department showing the final assembly of wing frames. The air connections for rivet squeezers and electrical receptacles for drills and other portable equipment are so placed that work may be carried on at almost any point with a minimum loss of time in making tool connections.

that we selected presses in preference to draw bench or rolling machinery because we were able to maintain greater accuracy of the sections made, and this accuracy is highly important for assembly purposes. It has been found economical to maintain accuracy of structural shapes within a few thousandths of an inch in all dimensions, because the saving of labour and elimination of delay in subsequent assembly work will more than offset the cost of maintaining such accuracy. This applies to completed assemblies as well as details, as it is highly important to be able to have immediate interchangeability wherever it becomes necessary to replace parts which are found to be imperfect.

One of the prerequisites for accuracy of the finished shape is that the width of the strips cut off from sheets shall be maintained within five thousandths of

an inch. This was somewhat finer than manufacturers of large metal shears were accustomed to furnish. However, upon our insistence they furnished us a shear which would maintain the width of strips within three thousandths of an inch in 18ft. lengths.

The point I wish to emphasise here is that by due process of analysis we confirmed our belief that metal is the fundamental material, consisting of duralumin and steel, and that the duralumin should be in the form of sheet.

Concerning steel, the analysis was by the same method but with somewhat different results, notably in the adaptability for making permanent fastenings and the sources of supply and delivery. Steel can be readily and cheaply welded both in tubing and sheet form. Steel tubing is available on short notice in any reasonable quantity, and its cost is low enough to permit a rather wide range of inventory, and for these reasons it appeared that tubing and sheet are the two major forms in which we should use steel.

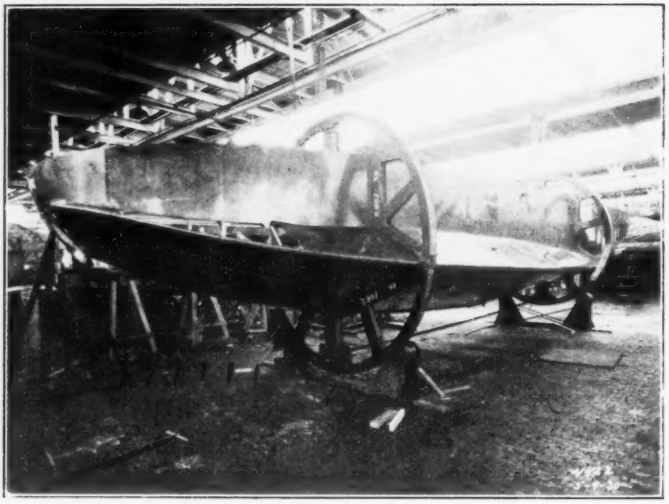

FIG. 12.

This photograph shows method of rotating or turning hull after bottom skin assembly has been completed. The fixture hinges at the centre and is readily removed after completion of operation.

Now there are several varieties of duralumin and many varieties of steel, and we did not feel qualified to guess which of these varieties would be most successful for use in an ideal aircraft manufacturing establishment. Once again we found the yardstick of suitability to be of great help. For example, there was offered a certain alloy of duralumin which was heat treated at the mill and which does not acquire its full strength and hardness until subsequently re-heated to about 350°F., thus permitting all forming operations to be performed while the sheet is relatively soft, and likewise avoiding whatever warping might result from the heat treating of complex assemblies. This sounded very promising indeed, but a combination of laboratory and service tests, together with a factory cost analysis, showed that the cost of protecting this alloy from harmful corrosion would be far greater than the saving effected by the beneficial characteristics of the material.

By a similar process of reasoning and experiment it was possible to select a certain analysis of steel. Considering the excellent economy of fastening steel joints by welding, it was first decided that the steel material must be pre-eminently suited for welding. To maintain the necessary weight-strength ratios the steel must also be one of the higher grade alloys, and by process of elimination in the laboratory it was found that chrome molybdenum steel of .25 to .35 carbon possessed the desired qualities in the highest degree.

I should mention that we did not perfect this method of analysis of materials for suitability in the beginning. From time to time additional progress has been

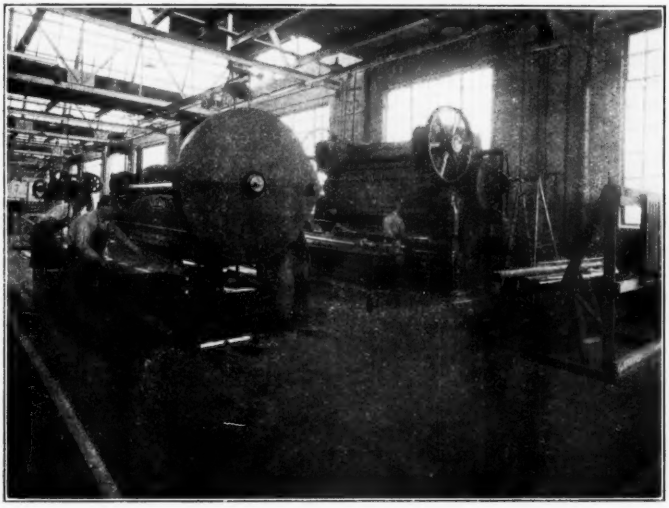

FIG. 13.

Photograph showing large brake and shear used in forming of special channels and forms. These two pieces of equipment are located adjacent to 16-foot nitrate heat-treating bath and levelling rolls. It is of interest to note the grouping of this piece of equipment in that sheets of aluminium alloy are taken directly from the furnace and passed through the levelling rolls after which they are sheared and formed in brake immediately while the metal is still soft, thus eliminating losses due to cracking of material. The size of the Niagara shear is 14 feet long and will satisfactorily shear mild steel up to ¼-inch thickness. The capacity of the large brake is 500 tons and with suitable radius will handle metal up to ½-inch thickness.

made, and it is now possible to determine with a fairly high degree of accuracy as to whether or not any given material is suitable at present, and for some years to come, for aircraft manufacture. We found it a most convenient way to avoid costly changes.

The same methods of reasoning apply to minor materials, and in recent years we have made important selections of materials for engine manufacture in the same manner.

In planning manufacturing processes it was found essential not only to determine upon certain major or fundamental materials, but equally important to

provide flexibility of processes so that in each of a variety of cases the most efficient material could be used as dictated by design requirements without interrupting manufacturing efficiency. In fact, as I have mentioned previously, this arrangement of flexibility appears to be a fundamental of good manufacturing.

There is no possibility at present of continuous reproduction in aircraft work. The term " Production " is applied rather loosely in America to the manufacturing of a specific article in indefinite quantities by a continuous process, and in such a process the only variation made is in the quantity of articles produced per day or per week, in accordance with the demands of the market. Many well-informed people doubt if aircraft will ever reach this stage of development, and everyone is, I believe, convinced that such a condition will not be reached for many, many years.

One is faced with the necessity of producing within the same establishment large airplanes and small airplanes, landplanes and seaplanes, and possibly in the future we may be called upon to construct other types such as the autogiro or helicopter.

FIG. 14.

An example of department flexibility compared to photograph numbers 4602 *and* 5038, *which is the same department at another time.*

While manufacture for commercial markets in the smaller types will undoubtedly afford a certain amount of continuity, nevertheless, even in the more favourable instances, the constant developments in design require rather extensive changes of models from year to year.

In contract work it is extremely rare to find any two lots of airplanes which are at all similar in the manufacturing sense. I use the term " manufacturing sense " to bring out the point that airplanes may be similar in appearance and function and still be radically different for purposes of manufacturing. We have recently completed two lots of flying boats for the American Navy which are scarcely distinguishable from each other in outward appearance, and yet none of the major parts of the two types are identical, with the exception of the wing tip floats.

In addition to the variation in types, one must also be concerned with the variation in quantity. It is quite common in any aircraft factory to find small lots and large lots of different types undergoing fabrication at the same time, or one may find a large number of small jobs being handled concurrently.

Still another variable which requires flexibility of manufacturing facilities is the variation between slack periods and rush periods, and it is clear that the ideal factory must be able to operate efficiently in lean periods such as the last few years, and still be prepared to expand quickly enough to profit by rapid improvements in market conditions, or should the necessity arise, meet the demands of war-time emergencies without time consuming confusion.

I have described the manner of determining materials that an ideal aircraft factory may use, and illustrated some of the requirements it will be called upon to accomplish.

In 1916, when the need for war aircraft began to be anticipated in America, I closed all my operations on the Pacific Coast and moved the organisation to

FIG. 15.

A sheet metal department that can be rearranged in a few hours. Section of sheet metal department showing assembly of fuel tanks

Cleveland. This location was selected in the midst of a manufacturing area, where skilled labour and supplies were plentiful. My bankers, anticipating considerable expansion of capital structure to meet the emergency of a war-time programme, felt that they would like to have my operations concentrated close at hand, and I was in agreement with this view.

Quite naturally, when laying out the Cleveland factory we strove for efficiency, but, to summarise the matter briefly, we found as time went on that the war crisis had caused us to view many important matters out of proper perspective, and so it came about that we began to formulate the requirements of a more ideal arrangement. Ample time was available in the following years to consider the problem, and a wealth of past experience from which to draw conclusions. We were able to recognise that certain predominating requirements had been present in each situation through which we had passed. The basic material, for example,

is important. Flexibility of operations is a second essential. Plant location and layout may well be the deciding factor between success and failure.

First, as to the location. Convenient railway connections are needed, of course. The 20 largest cities of the United States, without exception, have water frontage sufficient to permit operation of marine aircraft, indicating strongly that in America provision must be made for water deliveries and operation. A flying field sufficiently large to accommodate a volume of flyaway deliveries and testing should be included. It is important to study weather records to determine the percentage of foggy, stormy and other unsuitable flying weather. A high percentage of freezing weather is an important handicap to marine aircraft deliveries, and test work.

It seems important to know how close an aircraft plant should be to large centres of population.

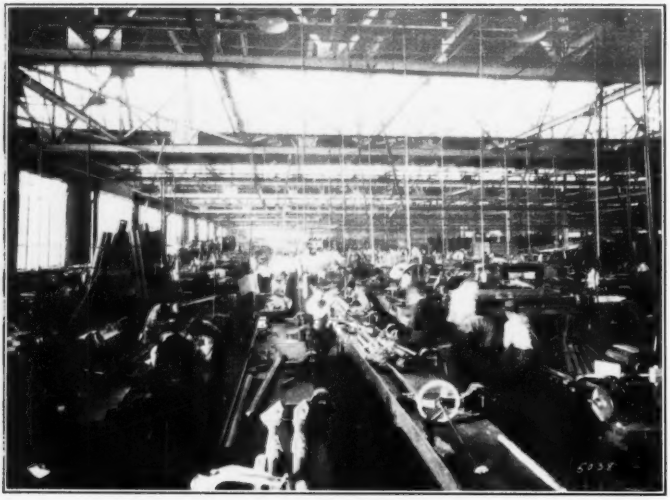

FIG. 16.
Another example of department flexibility.

There is a rather regular relation between labour rates and the mean distance which personnel must travel between factory and living place. The graph of this relationship for aircraft works is of the same general type obtained in all industries, being of parabolic form and expressed by a constant, such as the labour rate within the community, plus a variable factor proportional to the square of the distance travelled daily. However, upon gathering statistics from all available sources, and plotting curves, it was found that the prevailing wage rates in aircraft work were lower than the formula results. That led to some rather illuminating studies. The age of factory employees in aircraft work was found to be several years below the general average. The percentage of employees who travelled to and from work by automobile was considerably higher. Other lines of thought were developed that might lead readily to a profound study of aircraft employment sociology, which could scarcely be covered adequately upon this occasion. Suffice it to say we found that the type of workman who is interested in aircraft work is willing to make sacrifices for the sake of his calling. He is abreast or a little ahead of the times, and something of a pioneer. His daily

work deals with a form of transportation which makes distance less significant, and he is not greatly concerned by a few miles of additional travel per day.

It follows that the ideal aircraft factory, as far as personnel is concerned, need not be located within the confines of a large community, nor even immediately adjacent thereto, but it must be located upon the major highway system.

In giving due attention to major requirements one may sometimes overlook apparently minor items that are really important. The daily need of miscellaneous supplies of all kinds, and urgently wanted deliveries of special items are not to be treated too lightly. Most assuredly the plant location must be within easy reach of a wide variety of mechanical and electrical supplies.

Electric power and high-pressure water are essentials that must be found in the location, or else provided. This question may be reduced to definite terms

FIG. 17.

Duralumin sheet and steel tubing.

Section of raw stores stock room; packing cases in foreground containing aluminium alloy sheets. The materials in these boxes have all been checked, inspected and tested, and identification indicated on ends of same. The storage of these sheets in their original packing cases is to replenish stock bins.

by competent engineers, so that its bearing upon the choice of location is readily determined.

While main line railway sidings are essential for freight shipments, one should also consider the daily convenience of being able to receive or deliver express shipments from a nearby express office.

It is not especially necessary for an aircraft plant to be located in the immediate vicinity of the source of the major materials used. Instead, the element of minor delay in receiving materials should be taken care of by the basic materials selected, which ought to be of such a nature that a moderate inventory will not prove burdensome. Freight rates to source of major materials should be balanced against cost of maintaining suitable inventories. After computing the required inventory of minor materials and supplies or the cost of delay, it usually will be

found that neither alternative is acceptable, and the location of the factory must be within a few hours by motor-truck of some ample source of general supplies.

In addition to considerations mentioned previously concerning selection of the land for the factory site, one should also remember that the environment around a factory that may become a flying centre should be good aeronautically, and permanently so.

Briefly, we reached two abstract but fundamental conclusions concerning the desirable site. Sufficient space must be reserved for possible future expansion, both of plant and of flying operations, and, secondly, the land immediately surrounding the actual site must be under positive control. The same thought was felt to apply to the necessary water facilities.

Before seriously seeking an actual location which could match the theoretical needs we decided to investigate upon the most efficient forms of floor plan layout.

FIG. 18.

Multiple assembly method applied to hulls.

Naturally, the total floor space of the factory and the gross annual output capacity are factors of the greatest importance in individual cases. However, these factors are usually quite readily found in any given situation. Within reasonable limits they do not materially affect the general considerations, and for purposes of this discussion may be disregarded. Perhaps I should mention a factor that we had in mind concerning floor space. Since air is a low density fluid, it follows that the supporting surfaces of aircraft will continue to be large. If devices for increasing wing velocity, such as the autogiro, come into use, it seems true that the increase of lift will be used to improve load capacity, rather than to decrease the size of surfaces, and therefore floor space allowances should be generous. To give some specific substance to the problem I shall state that we had in mind a total of approximately one million square feet of floor space, of which one third was to be built initially.

The procedure in determining the factory layout consisted in first listing all conceivable requirements. The next step was to determine the probable annual increase in cost which would result if any one of these requirements was omitted,

and by this means it was possible to evaluate each requirement. As a basis for proportion we assumed that if all requirements were ideally met the net gain would be equal to the greatest profit one could expect consistently to derive from operations, and, conversely, if all requirements were omitted the sum total of increase in cost would be equal to the same amount. No doubt such sweeping omissions would result in substantial losses as well, but we were interested in the comparative relation of the various requirements rather than their absolute evaluation. For example, if a certain stockroom were to be placed in location " A," the increase in cost would be so many hundredths of a per cent. of the base figure. In location " B " the difference in cost could also be computed as a percentage of the base, and so on. For the evaluation of the less tangible items, such as facility for shifting departments, we accumulated data from past operations by determining the percentage difference in costs that would have become effective if such facilities had been available at the time in question, both as to labour saved and also as to reductions in overhead expense.

FIG. 19.
A semi-finished parts stock room.
Note bins for classification of small parts.

Eventually, by such a method, one is able to determine the value of each item within limits of accuracy that can be considered satisfactory.

The most fundamental item was indicated to be the flow-path of information and work from the initiation of operations to the final stage of delivery. If an analogy may be permitted, it appears that the resistance to flow of work is similar to the parasite resistance of an airplane, and the speed of the airplane is reduced from what it should be, not by any great single item of resistance, but instead by the sum of a great number of individually insignificant items.

The primary flow-path may first be determined in diagrammatic form. A convenient way to do this is with small paper discs, each labelled with a department name, or with the name of an important operation. The first disc is the raw material receiving platform, and the second is the raw material stockroom. It is quite workable next to place the airplane delivery platforms and final assembly

discs, thus permitting further progress to be made in constructing the diagram by working from both ends. In our arrangement three paths were led away from the material stockroom, one to the department of machine tools, one to the sheet metal department, and a third to the experimental department. Next to the machinery department we placed the welding and heat treating departments, and the bench work department. Proceeding from the other end of the diagram we placed the painting, finishing and covering department, and so on. Having eventually by this method completed the diagram, a cost analysis of the sequence of operations was next in order. Then rearrangements of the diagram and new analyses, until the most efficient layout had been determined. This process was repeated for various types of aircraft such as small and large landplanes, seaplanes, flying boats; and in some cases for variations in construction, such as cloth-covered wings, as opposed to metal covering, and so on. Our purpose in re-

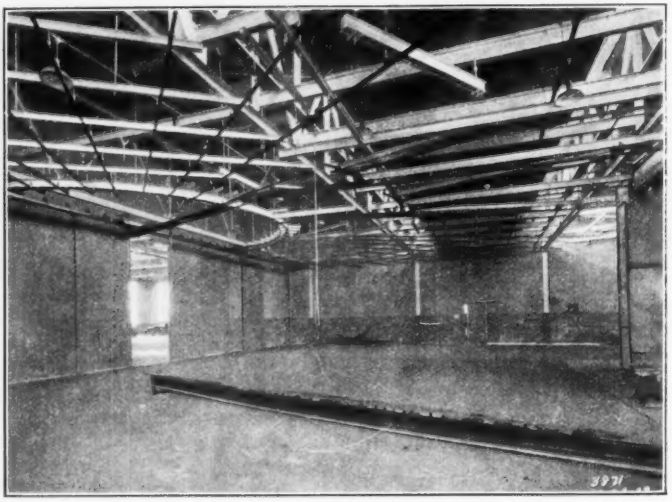

FIG. 20.

An overhead rack for drying painted parts.

This view shows section of finishing department before beginning of production work in factory and emphasises the overhead monorail system for handling of parts. This overhead system extends throughout all departments in the factory.

arranging the diagram was to discover the adaptability of a main layout for departmental changes. The analysis has shown that flexibility in this respect is second in importance only to proper flow-path. Aeronautics has been more prolific in the creating of new models than any other field of manufacturing, and one has come to accept this continual change of types.

We felt that flexibility of a high degree could be achieved if machinery, equipment and fixtures could be easily moved from one place to another. This demands clear space with few vertical columns and readily interchangeable power hook-ups. The spacing of columns is generally a function of the building dimensions. A square building contains the most floor space per unit of wall. Having in mind our ultimate plan of one million square feet, the ultimate building dimensions must

be 1,000ft. on each side. We laid out the portion for first construction to the dimensions of 1,000ft. by 300ft. By comparing floor plan costs with the structure cost of buildings a column spacing of 100ft. was found to be the correct figure.

To obtain ready interchangeability of machinery, a separate electric motor for each machine was included in the plans. All power lines can be run overhead with a net-work of outlets and drop leads to all points where machinery might ever be needed.

The same disposition can be arranged for all air pressure lines which are highly useful for the operation of small tools and riveting machinery.

It seemed to us that a factory with such arrangement could maintain an efficient flow-path of work to suit a wide variety of changes in type of construction.

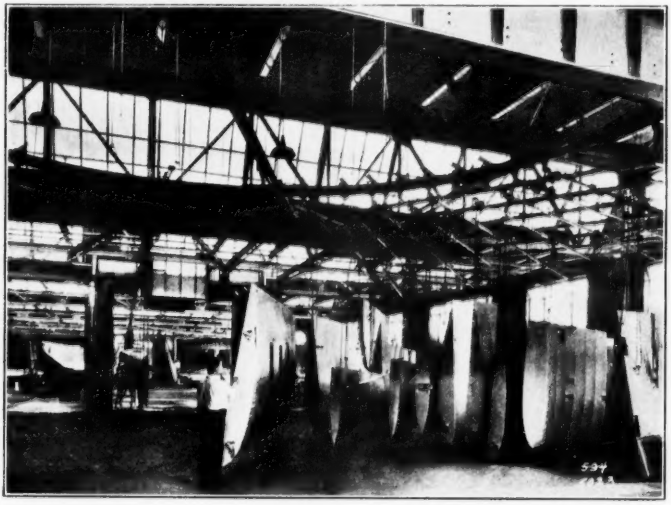

FIG. 21.

This view shows the overhead monorail system with a number of assemblies suspended while drying. In the background can be seen the spray booths where these parts have been sprayed and passed on via monorail after painting. Heavy assemblies are handled as easily by this system as the lighter ones. A flying boat hull is seen entering the spray booth to be given its final coats of paint.

A third fundamental indicated by methods of cost analysis is adaptability to changes in volume of work. We considered changes in volume which could be accommodated within a proposed floor plan by increasing or decreasing departmental space, and also changes which would require external additions to the total space. One of the principal considerations was to provide a method that would permit such changes quickly and without interruption to work in process. The flow of work will always be in the same general direction and certain basic departments, such as material stockroom, surface department, hull or body department, finishing department and a final assembly hall will always be required. It is therefore quite a simple matter to locate these departments in their proper relation to each other and, for the moment, leave all other space blank. By a moderate amount of re-arranging one can find the most suitable way in which the principal departments and the blank spaces could be enlarged externally and

still register properly with the proposed final layout of the entire plant. Our method consisted substantially in designing the entire ultimate floor plan, placing each major department so that it would be possible to increase any department to its ultimate size at any time.

Study of floor plans become very interesting and one can spend many months in the systematic consideration of aisle-space, overhead mono-rail for handling large pieces of work, storage spaces, lighting, ventilating, heating and similar branches of the problem too extended for detailed discussion. I would like to point out that in the case of each item there is one correct solution, and one only. No doubt the future development of industry will compel manufacturers in all lines of endeavour to strive toward the formulation of sound theory upon which such analyses may be based. I am not relating the story of our studies to you for the purpose of placing specific data upon record, because we feel that in spite of our most searching effort, many imperfections of detail have crept in, and that in the light of more advanced research in later years, these earlier

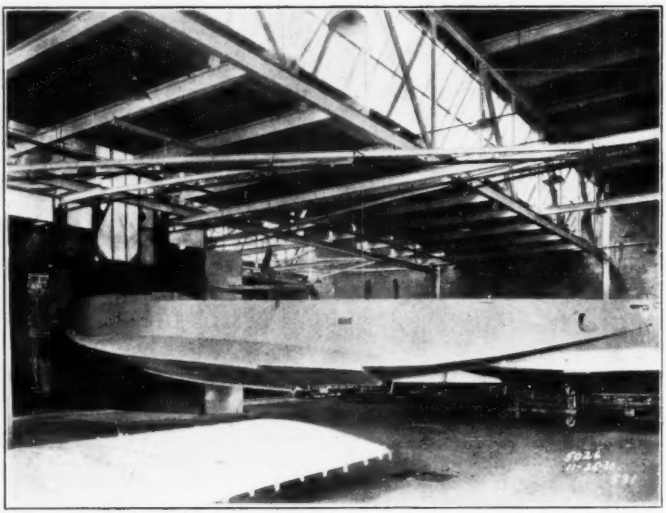

FIG. 22.
A hull mounted on overhead track entering the spray booth.

efforts will be but primitive at best. Nevertheless, we have become most thoroughly convinced that very definite gains are to be made by orderly analysis, and that manufacturing is indeed a science of most profound proportions. We feel most sincerely that one of the greatest obstacles to the advancement of aeronautics to-day is the lack of progress in the systematic study of manufacturing such as would be commensurate with the far-reaching progress made in studies of aerodynamics, and of aircraft operation. I want to submit for your consideration the bald fact that aviation is nearly as old as the automobile, and that the world is indicating rather plainly that it can live and promote its affairs if need be without aviation. Progress in the development of the airplane itself has not been lacking. We have ranges in excess of 5,000 miles, speeds now nearing the 400 mile mark, excellent reliability, load capacity measured in tons, and many other useful characteristics. Is it not reasonable therefore to suppose that the time has come to cast off old-fashioned philosophy and view the subject of manufacturing upon a more truly scientific basis?

One of our most unique studies was conducted to find the influences which slow down the flow of work. There are available from other industries many devices for speeding up work, usually in the form of incentives for workmen, or by shortcuts in operations. In some cases, even the effect of music upon workers has been investigated, output being measured against spirited tunes or pleasant melodies and so on. Our mode of attack was somewhat different. We felt that we should segregate and eliminate the retarding influences. As might be expected, general working conditions have much to do with employee efficiency, and I will have something to say on that topic a little later. Just now I would like to continue and tell you that we found the greatest retarding force to be lack of specific, definite instructions. Any confusion or misunderstanding as to exactly how and exactly when each and every part of the job should be done, resulted in losses of time.

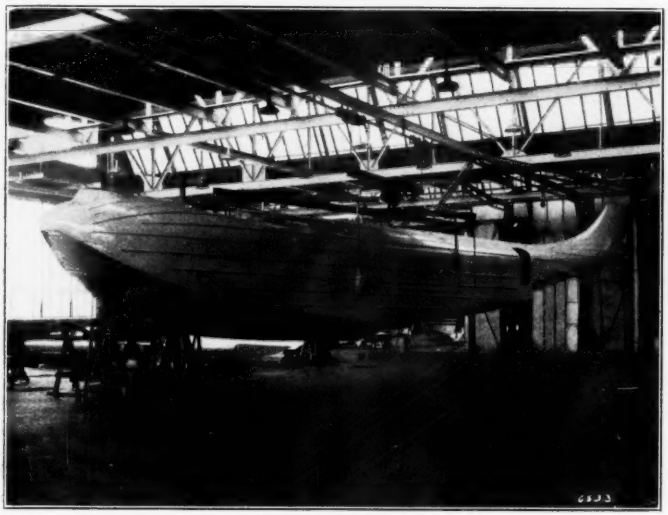

FIG. 23.

Handling a 60-foot hull by overhead rail system.

Now aircraft work is particularly subject to variations and modifications. Likewise one finds work of different characteristics going through process simultaneously. The details of such circumstances are familiar to all. The savings which could be effected by elimination of uncertainty are so great that it is clearly of fundamental importance to provide a thoroughly adequate system to accomplish the desired result. There are other sources of loss which we planned to eliminate by the same means.

For example, the setting and re-setting of tools and fixtures to accommodate successive lots of similar parts is costly. Frequently the time required to set up a job may be longer that the time required to make the pieces. It is important furthermore never if possible to lose efficient arrangement of floor space, such that one or more jobs would be held up waiting for floor space which was being used for other purposes at the moment. Timing the work, as it may be called, seems of great benefit.

Another retarding influence is caused by pieces which will not fit in their proper place in the assembly. They are always time consumers, and furthermore,

a drain upon good morale. A continuity of such cases has a bad effect upon assemblymen all out of proportion to the actual delay caused. Our customers, we knew, considered interchangeability of parts a great saving in maintenance cost, and while that was considered, of course, still it does not seem generally realised that accurate and ready interchangeability is a great time and cost saver for the manufacturer himself.

I have spoken previously of the flow of work. It may be regarded as the lifestream of a manufacturing plant. In the early days of 1910 to 1912 we built one or two airplanes at a time. Soon the quantities became larger so that it was no longer feasible to build one airplane as an entity and then begin at the beginning and build another. We very early chose the practice of first fabricating all the pieces and then setting about the business of putting them together.

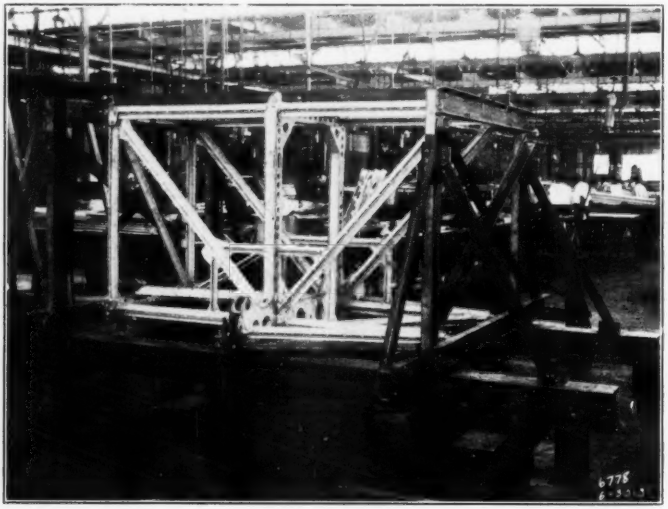

FIG. 24.

An example of sheet metal shapes and joints suitable for high speed assembly with rivets.

This is another example of the sturdy construction of assembly jigs so essential to the manufacture of units suitable for interchangeability with other planes.

During the war we were called upon to plan for several hundred airplanes of the same model, and it was at that time that we first began to study the flow of work and the elimination of influences that cause delay. This study has been carried on through many varieties of work and over a period of some fourteen years. I would like to pass over the rather long story of development and give you only the system as we use it to-day.

When any specific manufacturing programme is undertaken, certain orders are issued, covering the main divisions of the project. All Department Heads are furnished with the detail specifications of the aircraft, and the general arrangement drawings. If a delivery date for the first and each succeeding article of the order has not been set previously, it is set at this time, with due consideration of the capacity of the plant and the work in process. Then the entire manu-

facturing process is planned in reverse order, like a cinema film run backwards. If the shipment is by freight the first backward step is boxing, then disassembly, then flight test, then ground test, then assembly, and so on, all the way back to the very beginning. A certain portion of time is allotted to each operation, such that all operations shall be accomplished within the total period specified. This planning is done by a committee of about twenty-five executives, and all departments are represented. Work in the shop cannot begin until the engineering information has been released and we therefore arrange a similar schedule for the engineering work. I believe we were the first aircraft people in America to schedule our creative work. It is sometimes rather difficult to state on what particular day the correct idea for design will be conceived. When time is pressing an increase in engineeering man-power is helpful, although sometimes additional personnel may not be able to produce the needed invention without a protracted period of study, or if I may use the term, of incubation. In spite of this, our plan of scheduling design work has worked out very practically, and we endeavour

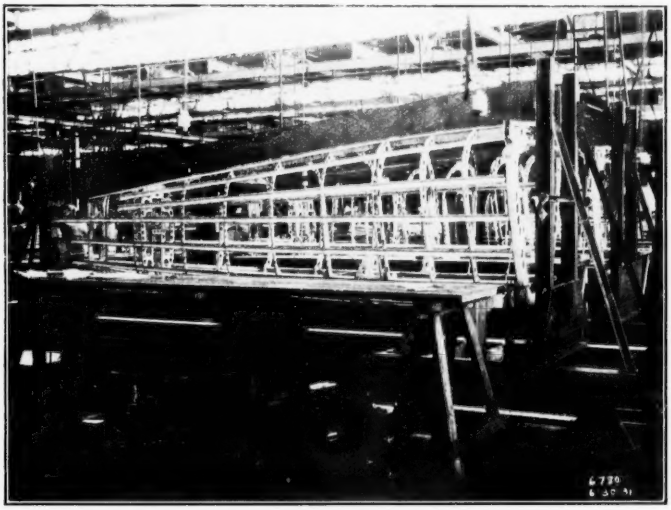

FIG. 25.

Showing method of assembling monocoque fuselage using extremely heavy fixtures to prevent distortion and insure interchangeability.

to attack the knotty questions early, depending upon logical analysis of design problems rather than spasmodic inspiration.

The shop schedule and the engineering schedule are joined harmoniously together and the entire plan is laid out in chart form. In former years this master chart showed only major items. As time went on more and more items were included. The rule is that anything which can affect the overall progress of the job must appear in the chart. If customer's approval of design is required, dates are set as to when it will probably be obtained. If a static test is needed it must carry its date of completion. The day on which the first engine will be required is named, and likewise when further engines will be needed and in what quantities. Should special materials be included in the construction, their arrival in our stockroom is predicted far in advance.

Groups from the master chart are sub-divided on detail charts.

Meanwhile all department executives are studying the floor space arrangements and working personnel which will be required to meet the dates which they themselves have set. Here the schedule begins to be useful because it permits each executive to plan the use of his space and equipment in time sequence. One might suppose that a department head would have mental reservations concerning the predictions made by his fellows in other departments, or even his own predicted dates. This possibility was realised early and we have set up means of making the master schedule as nearly " iron-clad " as is humanly possible. Our men have the utmost confidence in the dates set up, and habitually plan for events which are scheduled to occur, in some cases, nearly a year ahead.

Some further explanation of the actual functioning of the system will make their attitude understandable. I have mentioned that we first make all parts and later assemble them. This has now become common practice in many aircraft establishments. We carry out this procedure to the ultimate detail.

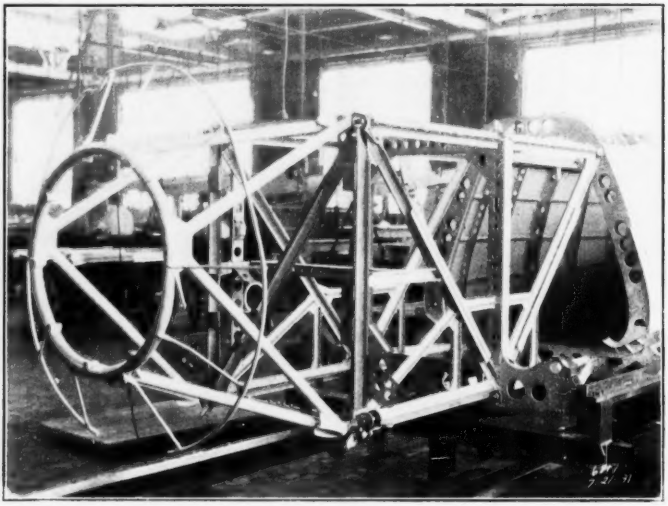

FIG. 26.
This photograph clearly shows the interchangeability of units which has been made possible by the use of heavy fixtures as shown in Fig. 25.

Individual drawings of every minute piece are necessary. For some models as many as six or seven thousand separate drawings are made, and the engineering cost is considerable. Nevertheless, if one will reflect that the determination of form, gauge and dimension is strictly an engineering matter it will appear that such work can be done far more efficiently by engineers and draughtsmen. The point being that it has to be done eventually and if not done in its proper place it becomes one of those factors which delay the flow of work in the shop. Thus we have in busy periods a substantial percentage of employees engaged in engineering work and feel assured that we are thereby reducing our total costs.

As a result of this method drawings may be released from the Engineering Department as rapidly as finished and checked for weight and dimensions. As a simple example, let us suppose that the rudder of a given airplane has been duly laid out and determined on the drawing board. Thereupon it is attacked by a group of detail designers, who make drawings of every separate piece of the

rudder. Immediately any piece-drawing is completed, it is checked and released. Now it may happen that rib No. 2 of this rudder is released first. Taken by itself, it might be difficult to decide just what part of an airplane it was. However, no one is interested just yet about that. Blueprints of the drawing are delivered to the Planning Department, to the Tool Department, the Inspection Department and the departments concerned in the actual making of the piece. With the Planning Department print goes the release sheet, and from the information on this sheet the Planning Department is able to issue orders to proper shop departments to make a certain number of pieces in accordance with drawing number indicated. At the same time orders are issued to the Tool Department to make such tools as are necessary for the particular piece in question. The Planning Department has also records of material-inventory, kept up to date

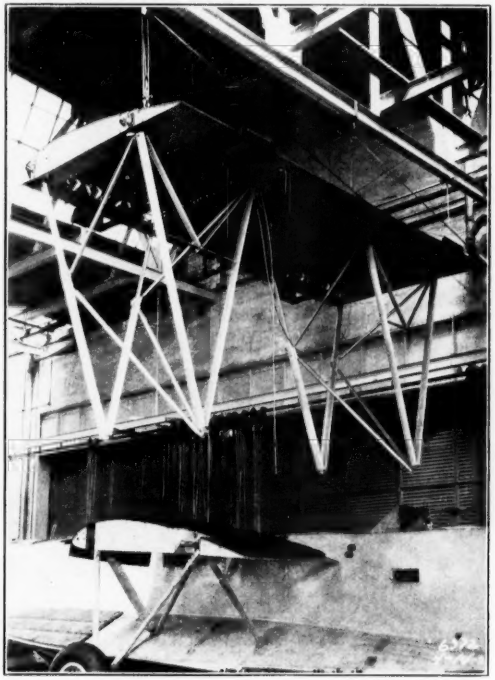

FIG. 27.

A complete unit being placed for final assembly.

from day to day, and proper deductions are made whenever material is ordered out.

The head of the department that will make the piece notes from his charts when tools and material will be available. When tools and material are ready they are delivered to him and he fills the order. It is his responsibility to see that his men, equipment and space are ready when the tools and material are delivered to him, because his time charts have told him when this would occur. Having filled the order he routes the pieces to the Finished Parts Stock Room. Here they remain until on a certain appointed day all the parts necessary to make the required quantity of rudders have been completed. Then all of these parts

are ordered out again to an assembly department, where they are put together. When complete they are again returned to a Parts Stock Room until finally ordered out to be assembled in place upon the airplanes. Inspection operations are carried out at appropriate times during the progress of the work. In actual construction this example is multiplied a thousand-fold, but the same procedure applies in each case, and the progress of each and every piece is in accordance with a definitely prescribed time sequence, so that each piece is in its appointed place in the process at the proper time.

Now as to the manner in which such an elaborate system of scheduling is made effective. It is clear at once that the value and essence of such a system lies in the knowledge of where each piece is at any given time, and whether or not it is moving in accordance with schedule. Another essential is the action to be taken if any piece is behind schedule.

In the manufacture, or rather building, of a single airplane, delay can readily be perceived. But 100 airplanes, for example, cannot be built singly in succession

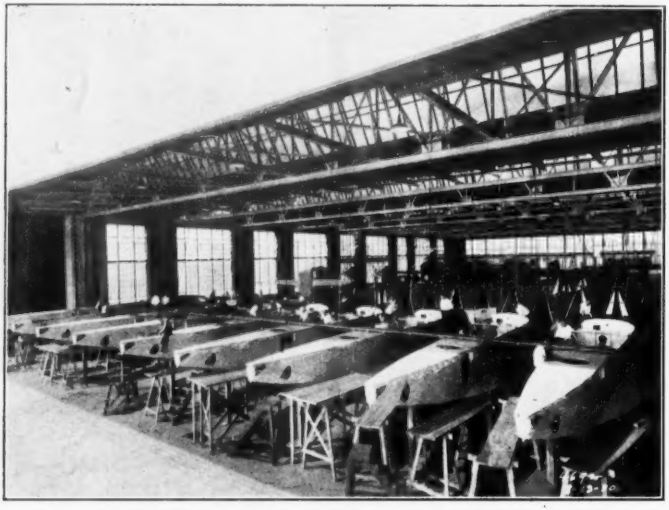

FIG. 28.

Installation of equipment by multiple assembly method. View of the assembly floor showing progressive method of assembling of parts in hulls.

because the total time would be a substantial number of years and the airplane would assuredly be obsolete before the order was completed. Reproduction of a vast number of apparently unrelated pieces becomes a necessity, and it is surprising how inevitably delay will accumulate under such conditions. It is fatal to wait until the delay actually occurs. It must be anticipated and prevented.

Once each week the same committee of executives that made up the schedule meet for the purpose of discussing anticipated delays in schedule. Reinforcements of men, equipment, space or such other help as the situation may demand are provided for then and there. This committee of manufacturing executives has witnessed the detection and elimination of so many impending delays that they have acquired a most wholesome confidence in this time sequence system.

The system I have described can be applied in the most minute detail.

The weekly meeting is a most effective manner of providing means whereby anticipated delays may be avoided. We maintain in addition a staff of people whose business it is to follow up all parts and to expedite matters between weekly meetings. Various ticketing methods are employed to record the progress of each piece and partial assembly in its path through the factory, and these tickets are posted daily against dates previously set down. The factory staff can readily determine whether the rate of progress is satisfactory or not, both generally and in detail, at any given time.

Naturally enough such a system is not to be perfected nor mastered in a moment. We are continually learning lessons from the information that comes to light through this system. It tells us what designs are difficult or costly,

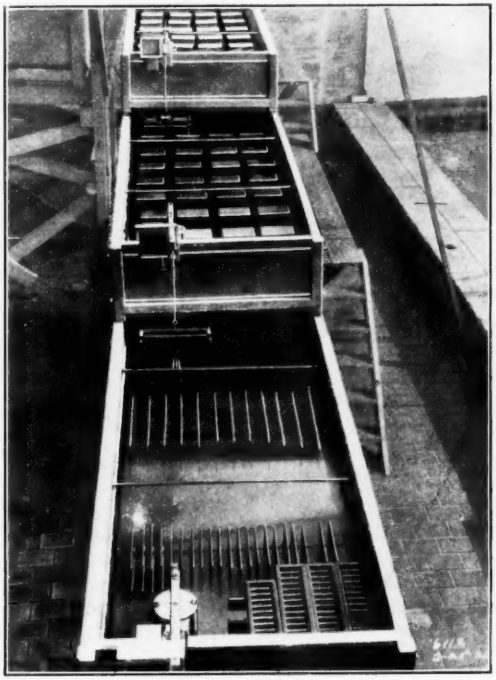

FIG. 29.

An example of selective testing to determine suitability of materials for corrosion resistance.

what departments are crowded, which department heads are most efficient and many similar facts that might not receive attention so readily, if at all.

The importance of the major materials in such a plan perhaps will be more clear now than it was when I was describing our elaborate pains to select proper materials. Having made sure of major materials we can carry an adequate supply with assurance, and having such a supply can avoid the majority of delays that occur from shortages of material, or from material that proves faulty at an inconvenient time.

It will also be clear, I hope, how such a system permits the economical planning of floor space well in advance. Ample time is afforded for shifting

of department layouts and capacities, particularly if proper attention has been paid to facility for accomplishing such rearrangements in an efficient manner. Suitable basic materials, a proper factory layout, and a systematic plan for determining manufacturing needs in advance will largely eliminate worry over the changes that occur in the continual development of aircraft.

Before continuing with other topics I would like to show how the physical arrangement of departments dovetails with the flow path of information. In the front corner of the building is placed the Engineering Department. The north and west sides of this department are walled with glass, daylight from these directions being best for draughting in the northern hemisphere. On the south side is the Experimental Department and on the east is the Planning Department and the Tool Design Department. This close arrangement permits the immediate contacts necessary for active co-operation. Design information

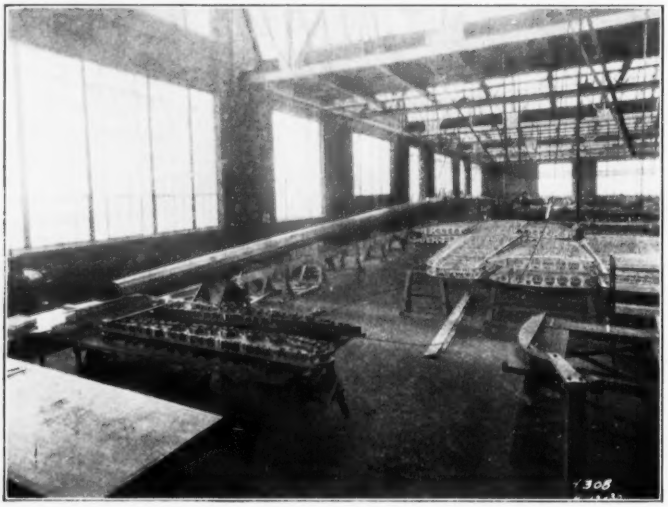

FIG. 30.

The duralumin mast of the cup defender "Enterprise," showing deflection test.

This mast was of riveted construction and built of high-strength aluminium alloys and high-strength alloy steel fittings for the yacht "Enterprise," defender of America's Cup, 1931.

is received by the Planning Department and distributed into flowing channels with no loss of momentum. Designers of fixtures and jig tools may observe details of design while still on the drawing boards and prepare their work accordingly. The advice of our tooling and manufacturing experts is frequently sought when considering types of construction or design details.

One may wonder how creative development could be carried on with a system so entirely predicated upon orderly manufacturing practice. We tried years ago to manufacture quantities of aircraft in a shop designed for building rather that manufacturing. Later on in our Cleveland Plant we had but indifferent success in our attempts to develop experimental aircraft in a factory designed primarily for manufacturing in quantities. The airplanes were successful enough, but the costs were not. From these experiences, we have definitely concluded

that a successful establishment must develop its new models separately from the quantity work.

At present, in Baltimore, we have an Experimental Department within the main plant, completely separated from the production shops by substantial tile walls. Here engineers and constructors may solve their problems by calculation and layout; by dummy models or by static test. Scheduling is not seriously attempted until the ground work has been laid and all indeterminate questions reduced to a basis of decision.

The departments of Engineering, Experimental Work, Planning and Tooling form a sort of nucleus of live information and a trend of development which have far-reaching effects upon the entire manufacturing programme, and for these reasons we have concentrated them together and close to manufacturing operations.

In the earlier part of this lecture I mentioned that the staff organisation was held to be a fundamental factor. Unquestionably, it is true that the experience of a welded group of executives, their training, resourcefulness, character and judgment form the most prized asset of any firm. However, I had reference more particularly to divisions of responsibility that we have found proper for efficient results. One must recognise two predominating divisions of the business of manufacturing aircraft. The airplane was for many years just an invention and even now scarcely has passed beyond the stage where it may be looked upon as an engineering feat. The development of engineering thought in aeronautics has, and must continue for many years, to have a predominating influence in the aircraft industry. Secondly, as I have been endeavouring to emphasise, the manufacturing processes by which aircraft are physically produced are susceptible to the most profound and painstaking study. Our two primary problems are these: first, in what form and to what dimensions shall the aircraft be built, and second, what is the best way to give substance to the picture the designer has presented.

We therefore divide our organisation first into Design and Manufacturing. Furthermore, we need materials and attention to our finances. Departments of procurement and treasury follow naturally. To sell our product we need expert salesmanship. We consider these five divisions adequate to cover the present situation.

Our manufacturing organisation is of the usual American type, patterned after the line organisation of military forces. The smaller tactical units of the military have their counterpart in our various departments. These department heads report to supervising executives, who, in turn, receive instructions from the factory manager.

One of the unusual variations we have successfully used is to place the design of fixtures and tools under the control of the factory manager. While this part of the work is primarily design, the factory will use the resulting tools, and if they prove inadequate or faulty the responsibility is already fixed.

All work of a technical nature is concentrated in the Engineering Department. Here we have obtained best results from a combination of the group system and the project system. The groups consist of from two or three up to 25 men under one head, who is responsible for the correct design of all details for a given part of an airplane, such as wings, hull, body, power plant, equipment, armament, and so on. A project or co-ordinating engineer is assigned to each model to co-ordinate and direct the work of all group heads. He is responsible to the Chief Engineer for all parts of the design. Our engineering staff includes an assistant chief engineer whose duty it is to direct all staff activities such as stress analysing, weight control, structural and flight testing, preparation of specifications, and the like. All group heads are directly under the control of the Chief Draughtsman, who is the drawing office manager and liaison between project engineers, group heads, and shop executives.

We think it advisable to take as much thought concerning expansion and contraction of our staff organisation as we do of the variations in our space and equipment requirements.

In laying out the new Baltimore Plant we were able to incorporate some of the principles that apply to better working conditions. We have found that definite gains can be made in productivity by this means. As a high percentage of our employees come to work by automobile we have been careful to provide ample parking space on prepared surfaces, surrounded by protective fences, and conveniently located. The initial parking unit accommodates approximately 1,000 cars in orderly fashion.

We have spared no pains to perfect the outward appearance of the plant, and have found that such efforts are reflected in the pride and confidence which employees feel in the establishment.

In each department is a group of units consisting of electrically-controlled time clock, individual coat lockers, wash fountain, refrigerated drinking water unit, toilet unit and desks for foremen and their clerks. By this arrangement every department is an independent unit. Each employee's time begins only when he reaches his place, and there is no occasion for him to be elsewhere during the day except on matters of company business.

A special design of high and low monitor roof was worked out to give good lighting for the entire factory, with glass sides in each monitor. To relieve glare, all glass facing south is of the anti-actinic type.

All electric lighting is from above, and lights are grouped in sets of four 250-watt lamps on each switch so that any specific area may be illuminated without unnecessary loss of current.

Heating and ventilation are accomplished by a newly-developed unit system. The heating furnaces are arranged in line along the western side, this being the colder in winter. Heated air is led in floor ducts across the factory toward the east, with frequent outlets in the aisles. In hot weather the blowers are used to circulate fresh air from outside to all points within the building, reducing humidity and increasing oxygen content. Ventilator outlets are arranged systematically over all the roof, to complete the circulation system.

Notable improvements in morale have resulted from attention to interior appearances. All steel work is finished in aluminium enamel instead of the usual red or black. A high percentage of glass has been included in the walls and roof. All intervening wall spaces are of cinder-block finished in an agreeable light buff colour.

The entire factory floor is made of creosoted cedar block, laid with end grain exposed, on a concrete base, and the result is a remarkably even and smooth surface of low sound producing characteristics and minimum floor reflection.

The general result is attractive to workmen of the highest ability and character, and I feel that the results in perfection of work and elimination of losses which follow from efforts of this kind to provide more ideal working conditions cannot be too strongly emphasised.

A most prominent problem in the minds of manufacturers at present is tooling, which is the name commonly used in America to designate all means and devices for accurately reproducing a quantity of duplicated parts. The question ordinarily is to determine how much tooling expense is warranted in comparison to the savings to be derived. The higher labour rates which prevail generally in the United States emphasise the benefits of proper tooling. In fact, design, tooling, and labour costs form a sort of triangle, each being influenced greatly by the other two. As quantities become larger in the future the labour charge per piece will be more important than either the design or tooling costs. In the present situation the prediction of quantity is difficult. If a certain model is tooled only for a conservative output, and subsequently becomes popular, it may be necessary to decide whether to interrupt production for re-tooling at a critical time, or to

continue with tooling equipment planned for smaller quantities. Over-tooling for a model which fails to achieve an anticipated demand also may prove disastrous. As a matter of insurance it appears to be advisable to carry the necessary staff of tooling experts for the purpose of actually calculating costs with varying degrees of tooling. If the quantity is predetermined by a customer's order, or by market analysis, it becomes possible to calculate with satisfactory accuracy the amount of money which can be spent economically for tooling. As a simple example, suitable calculations will show whether a given fitting, in specified quantities, should be made by hand, or part by hand and the remainder by machine, or whether forming dies should be made for entirely machine fabrication. Too much standardisation in tool equipment may lead to design compromises which retard genuine progress.

Tooling has a particular value in providing ready interchangeability, and this factor should appear in the analysis. A great deal of time may be saved by it in assembly processes, and tools which may not be warranted by direct saving of labour in piece manufacture, may still pay for themselves generously if they prevent delays in assembly operations. The customer will appreciate the reduction in his maintenance costs brought about by ready interchangeability. This goodwill may in many cases warrant tool expense otherwise unjustified. I have wished to point out a few of the many ramifications of this problem, and emphasise it because of its ever-increasing importance.

Another problem that I feel is entitled to wider attention is cost analysis. Not cost analysis which only accumulates a supply of dusty records, but rather cost data which throw a strong light upon parts of the work that are unduly expensive. Now cost in manufacturing is closely analogous to weight in design, and it is quite common practice to find aircraft engineers exercising control over aircraft weights. The plan generally employed for weight control consists of dividing the aircraft into suitable groups, making an allotment of weight for each group. This weight allotment is redivided until each item of the group has a certain weight set up for it. After the design of any item is completed, the weight is calculated and compared to the weight allotted. If the calculated weight is the greater, a reduction by redesign is ordered. If nothing can be done to remedy the situation a debit weight is accepted temporarily. However, should the calculated weight be lighter than the allowance, a credit is recorded, and debits of like amount may be accepted. By this system the engineer is aware of the status of weights. If too many debits accumulate a searching redesign is inaugurated to wipe out the overweight. One can readily appreciate the great value of a similar running analysis of cost data. Consideration of such matters has convinced me that more of such systematic study habitually applied to design may be profitably applied to manufacturing. It appears entirely feasible to budget cost in the same manner as weight, and efforts in this direction have brought about savings that were not suspected. By careful selection of the groups to be budgeted the accumulation of cost figures may be greatly simplified. In such schemes as have been worked out thus far it appears best to separate such items as design, tooling, fixed charges and overhead expense. Labour may readily be divided in groups, such as body or hull, wings, landing gear, surface controls, shipping boxes, testing, etc. Labour tickets for each group may carry a distinctive colour or designation and a weekly summary may be made for comparison, with cost allotments previously worked out. Thus any group which is over-running its allotment may be immediately investigated before great damage has been done.

A further problem which is receiving attention in these present years is whether military work and commercial work can be carried on concurrently. From my experience it appears that the division is not primarily between military and commercial work, but rather between job construction and continuous production. By job construction I refer to orders for a certain number of airplanes built to a given specification. The problems of design, construction and inspection are the same in job work no matter who may be the customer. It is true that military

types require installations of equipment and ordnance that are highly specialised and which require continuous consultation with the various technical experts of the Government.

Speaking purely from the standpoint of the manufacturing problem, one recognises a pronounced difference between the requirements of design, planning, tooling, and fabricating for a given lot of airplanes and the requirements for continuous reproduction of a standardised type. In job lots, engineering and tooling must be closely proportioned to the quantity given in the order, while the factory layout and equipment must be of such universal capabilities that a wide variety of types can be undertaken with economy. Continuous reproduction of a standardised type, however, justifies a far greater budget for design and tooling costs, in view of the greater quantity, and likewise permits the use of machine equipment and floor layout particularly adapted for construction of the one or more types that have been selected for standardisation. In job lots the attention of manufacturing and planning executives will be directed largely toward ways and means of constructing the aircraft ordered, whereas in continuous work there is greater opportunity of examining the efficiency of manufacturing in more minute detail. It frequently happens in job work that better means are found for making the necessary parts, the only drawback being that the order has been, or will be completed before the improved methods could be inaugurated.

The subject of aircraft manufacturing development is far too broad to permit analysis on this occasion of all its component details. I feel that aircraft manufacturing is now, or will soon be, passing through its most critical stages, and I trust that I have persuaded you somewhat toward my view that we should apply more and more systematic research upon the causes and effects of the various factors in manufacturing. I feel that there is still much to be done to accurately determine the far-reaching influence of materials, floor plan arrangements and planning systems. One wishes to have more accurate and comprehensive data concerning correct staff organisation, working conditions for personnel, analysis of tooling requirements, and methods for cost control. There would, perhaps, be great mutual benefit in some agency, beyond casual meetings, through which enlightening facts could be exchanged.

I trust that I have had your indulgence for the many references to my own personal experience, for after all there is little published information upon the subject. I am deeply appreciative of the honour you have accorded me in requesting an expression of my views, and only hope the considerations presented will promote further thought and bring forth information of far greater value upon the subject of aircraft manufacturing.

Mr. H. E. Wimperis, C.B.E., F.R.Ae.S., Vice-President of the Society and the Director of Scientific Research at the Air Ministry: He rose to propose a very hearty vote of thanks to Mr. Martin for his lecture. He would like to read a cabled message sent on behalf of the Society to Mr. Orville Wright and Mr. Orville Wright's reply to it. The cabled messages were as follows:—

> *To Mr. Orville Wright.*
>
> We the President and Members of the Royal Aeronautical Society, with our guests, will on Wednesday next be assembled again under the wings of your historic aeroplane to listen to a lecture delivered by Glenn Martin, your compatriot, in memory of your distinguished brother. We have heard with interest that the advancement of the science of aeronautics still claims the major portion of your time, and join in sending you most cordial expressions of goodwill.
>
> Fairey, *President.*

From Mr. Orville Wright.

> Heartiest greetings to all assembled to hear our good friend, Mr. Glenn L. Martin, deliver the Wilbur Wright Lecture. What would be Wilbur's astonishment could he see the progress that has been made in aviation, and especially the record made by the British in the last Schneider Cup, which was more than three times the speed he and I dared dream of back in his day. My congratulations on this wonderful record.
>
> ORVILLE WRIGHT.

He recalled that when he had visited the United States two years ago, primarily with the object of visiting the research stations, every facility had been granted him, and he had also visited some of the factories there, but he was sorry that he had not had an opportunity of seeing Mr. Martin's works. It seemed now, however, that had he visited the works, he would have found it almost impossible to return; to have visited a place having so delightful a name as "Maryland" would have proved so attractive that to return would have been almost out of the question.

A point to be borne in mind when considering the problems confronting any manufacturer of aeroplanes in the United States was that, judging from what he had been told when in America, the American pilot treated his aeroplane just as an American owner of a Ford car treated his machine. When machines were to receive such very drastic treatment it became necessary that the manufacturer should take precautions of the most extreme character, for one felt that unless such precautions were taken it would be quite impossible to build machines which would be really safe. Mr. Martin was able to satisfy that very difficult requirement, and he deserved congratulations.

Lieut.-Colonel J. T. C. MOORE-BRABAZON, M.C., F.R.Ae.S., M.I.Ae.E., Vice-President of the Society: In seconding the vote of thanks, it seemed to him, as an unemployed politician, very nice to be able to address a meeting with the knowledge that everyone present would support the proposition put forward. In the realm of aeronautics he was merely a looker-on, and he had come to the conclusion that those people who made aeroplanes in large quantities were very rich men. All who had listened to the lecture knew now how to make aeroplanes in large quantities successfully; consequently, they were all potential millionaires, and no doubt had made up their minds to establish aircraft factories.

The vote of thanks was carried with acclamation.

INJECTION, IGNITION, AND COMBUSTION IN HIGH-SPEED HEAVY-OIL ENGINES

BY

S. J. DAVIES, PH.D., M.SC., AND E. GIFFEN, M.SC.

March, 1931

[This paper was the subject dealt with at an unique meeting of the following eleven Scientific Institutions at the Institution of Mechanical Engineers on March 31st, 1931:—The Chemical Engineering Group, the Diesel Engine Users' Association, the Institute of Fuel, the Institute of Marine Engineers, the Institution of Engineers-in-Charge, the Institution of Mechanical Engineers, the Institution of Petroleum Technologists, the Junior Institution of Engineers, the Royal Aeronautical Society, and the Society of Engineers. As the Meeting was convened by the Institution of Automobile Engineers, the chair was taken by Mr. W. A. Tookey (President-Elect), who, after explaining the inception of the meeting, introduced Mr. L. Pendred, Past-President of the Institution of Mechanical Engineers, to the chair. Mr. Pendred then opened the meeting with the following remarks:—It has always been one of the aspirations of my life to see more co-ordination between the great Institutions connected with engineering, and such a meeting, to me, is very delightful to see. I think this meeting may honestly be described as an omnibus meeting, and I am here only as the conductor! A conductor, as you know, has very little to do with the course of the vehicle, but he has something to do with the time which it takes in that course, and one of my duties to-night will be to see that we get through some time before the early hours of to-morrow morning. I think I should say to you in that connection that you must regard the engine of this particular bus as a real Diesel one, and not a Hornsby-Ackroyd engine, and that as far as possible you will compress your hot air to the limit.]

Although there is one successful high-speed heavy-oil engine employing air injection, it will not be disputed that the present rapid development of this type of internal combustion engine would not have taken place if a high-pressure air-compressor were an essential accessory. It is perhaps well to emphasise that from the beginning designers of engines of the pure "compression-ignition" type have striven after airless injection of the fuel, the first successful application in this connection being that of Sir James McKechnie, of Vickers, Ltd., in 1910. Subsequent development work by Professor Hawkes and others under the Admiralty brought this method to practical success on submarine engines, and it is interesting to note that as late as 1920 almost all experience with airless injection had been gained in this country.

Engines which are the lineal descendants of these early engines, namely, those in which the fuel is injected directly into a combustion chamber of simple form, and known conveniently as the "direct-injection" type, constitute an important section of those engines working successfully at high speeds. The second main type of high-speed heavy-oil engine, the "ante-chamber" type, is a parallel development, and whereas the direct-injection type has worked downwards from large outputs per cylinder, the ante-chamber design was originally used in smaller units, its application to higher speeds of revolution being the path of advance. The third main type, that employing an "auxiliary air chamber," although, by virtue of the divided combustion chamber, apparently related to the ante-chamber type, may be more properly regarded as a special solution of the problems of the direct-injection type.

In stating the problems met with in high-speed heavy-oil engines, the reasons why successful airless injection was brought about only slowly are readily seen. Assuming that, as is the case in its application to transport, the engine must be flexible both as regards speed and load, these problems are: (1) The metering of the fuel to the engine in the correct quantities at all desired speeds and loads;

(2) the delivery of the fuel into the cylinder under these conditions at a suitable pressure and at such a rate that combustion may proceed so that, on the one hand, it is complete at a point in the expansion stroke sufficiently early to ensure good thermal efficiency, and that, on the other hand, the rise of pressure behind the piston is neither irregular nor too sudden, conditions which would cause " roughness " in running; (3) the suitable sub-division or atomisation of the fuel and the suitable control of its direction and penetration; and (4) the control of the motion of the air in the cylinder so that the mixing of fuel and air may lead also to satisfactory rates of combustion.

The successful solutions of (1), (2) and (3) without the use of injection air really constitute a triumph of mechanical engineering; they involve fuel systems working under exceedingly high pressures and, under these conditions, working parts made to so high a degree of precision that the extremely fine control necessary over the rates, and pressures, at which the fuel is delivered, is ensured. That this development in engine design has had, therefore, to await the contemporary advance in workshop methods is one factor which has determined its rate of progress.

A second factor controlling the development concerns problem (4), the satisfactory mixing of the fuel and the induction air. In this connection it should be remembered that the principles underlying the operation of heavy-oil engines employing air injection were, ten years ago, only vaguely understood, in spite of the satisfactory performance of such engines at that time. Bearing in mind the part played by the injection air in the mixing process in air-injection engines, it was thought that designs which dispensed with blast air would involve problems very difficult of solution, and it is not surprising that, only five years ago, the view was commonly held that the *indicated* thermal efficiency of the airless-injection engine would *never* approach that of the air-injection engine. Experimental work dealing with various aspects of the processes of injection, ignition, and combustion has contributed to the great advance made, and to-day, much more is actually known concerning these processes in airless-injection engines than in the type using blast air. It is hoped in this paper to indicate the present state of knowledge, but it is unnecessary to emphasise that, in covering so wide a field, it is impossible to touch extreme depths at all points of the subject; for instance, little attention can be given to the different classes of design, which have, in any case, been dealt with elsewhere.[1]

To give order to the treatment, it is convenient to sub-divide the subject roughly under the two headings: processes in the fuel-injection system, and processes within the cylinder. Under the former will be considered the conditions in the pumps, connections, and nozzles, the actions of which are all mechanical in character. Under the latter heading will come the mixing together of the fuel and air, the ignition of the fuel, the complete combustion of the fuel, and the resulting change of pressure and temperature in the working substance. These operations are thus partly mechanical and partly thermodynamical. In general, it may be said that there is no need, under the first heading, to differentiate between the three main types of engines, the " direct-injection " engine, the " ante-chamber " engine, and the " auxiliary air-chamber " engine, since the principles involved are common to all types. At the same time, since the pressures and rates of injection will not be the same in all cases, details of design will be different. But under the latter heading there are marked differences between the actions with the three types.

The Fuel-Injection System

Although the functions of the pumps, the piping, and the nozzles are obviously different, there are certain principles which must control the design of a fuel system as a whole. By far the most important consideration in the pumps and

[1] See *Engineering*, October 24th, 1930.

the nozzles is the extreme precision in manufacture referred to earlier; the parts must, therefore, be so proportioned that they can be made to this degree of accuracy. Further, having been accurately made, they must be capable of performing their functions of metering and delivering the fuel under the desired conditions also with extreme accuracy and regularity, and they must, obviously, be capable of continuing to do so over long periods without attention.

Factors which will tend to prevent such satisfactory performance are wear of the parts, elastic deformation, both under dynamic loading and under fuel pressure, and the compressibility of the fuel. In connection with wear, one of the objections urged against the high-speed heavy-oil engine is that it is too much to expect that the extreme precision necessary for the working parts of the fuel systems can be maintained over any reasonable length of time. Great care must certainly be given to the hardness of such working parts as pump spindles and barrels, and, as far as possible, all mechanical impurities in the fuel likely to lead to abrasion must be removed by careful filtering. But, after that, fears of a rapid reduction of accuracy by wear are not borne out in practice. Evidence of the constancy of performance of fuel pumps is given in Fig. 1, kindly supplied by

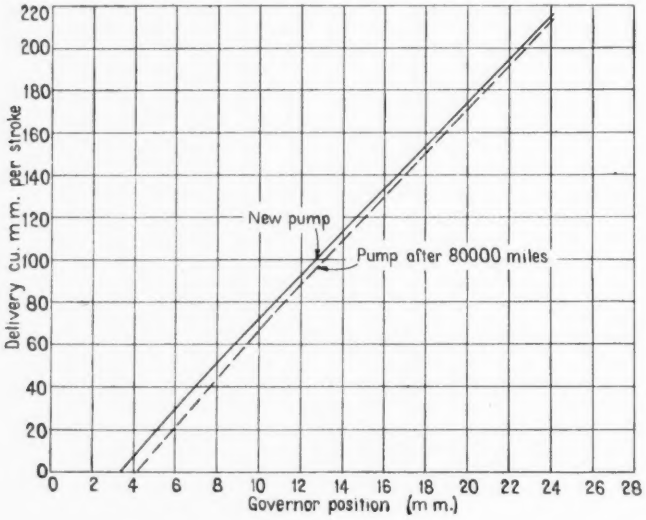

FIG. 1.

Fuel pump performance before and after service.

the Robert Bosch A.G. This shows curves from two tests upon the same fuel pump, the first as delivered new, the second after running 80,000 miles in a goods lorry. As regards elastic deformation, this, provided its importance is realised, may be rendered negligible in effect by relatively straightforward design. The effects of the compressibility of the fuel, however, are complicated by the fact that, in addition to the reduction of volume of the fuel and the distortion of the piping, etc., under the direct fluid pressures, it may be necessary to take into account the action of pressure waves in the system.

The reduction of volume of the fuel under pressure is obviously proportional to the volume of fuel in the system, so that the volume of all pumps, passages, etc., should be made as small as possible. Passages should thus be smooth and direct, and of the smallest cross-section consistent with the desired velocities

of flow. And, since even minute quantities of air increase considerably the compressibility of the oil, there must be no possibility of air pockets in the system, and any air contained in the fuel—a condition inevitable in transport over rough roads—should be removed by filtering.

The information available concerning the physical characteristics of even the commonest fuels is by no means complete. D. H. Alexander's results for the compressibility[2] of a fuel oil up to pressures of 5,000lb. per sq. in. are given in Fig. 2, but re-plotted as percentage reduction of volume on a base of pressure, and also as the bulk modulus of elasticity. From this it will be seen that the compressibility varies very little with pressure. R. S. Jessup[3] has investigated the compressibility and thermal expansion of a number of petroleum oils, but although his temperature range was from 0° to 300°C., the pressures only reached 700lb. per sq. in. Fig. 3 shows the results from two gas oils of widely

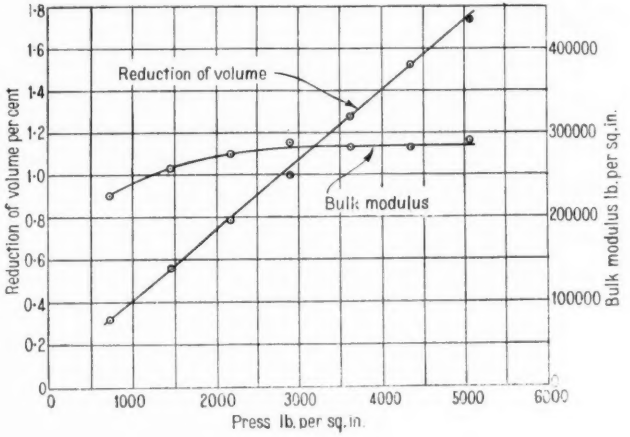

FIG. 2.

Compressibility of fuel oil—Alexander.

different densities and viscosities. He also found that the mean compressibility of gas oil decreases only slightly with increase of pressures, but as the curves show, the compressibility is very susceptible to changes of temperature, and is widely different for the two oils. Jessup found also that petroleum oils of the same density and viscosity had, within narrow limits, the same thermal expansion and compressibility.

The question of the pressure waves set up in the fuel pipes is one that to-day is much under discussion. One point that must be considered, since it determines the velocity of propagation of the wave, is the relative influence of the compressibility of the fuel and the increase of volume, *i.e.*, the elasticity, of the pipe under pressure. For instance, taking figures typical of present practice, assume a fluid pressure in the pipe of 2,000lb. per sq. in. and a ratio of external diameter to bore of the pipe of 2—so that it must be treated as a thick cylinder: with a steel pipe, the increase of volume of the pipe under these conditions is 0.025 per cent., and the decrease of volume of the oil is 0.75 per cent. So that the increase of volume of the pipe is about one-thirtieth of the decrease of volume of the oil and, therefore, the bulk modulus of elasticity of the oil " in the pipe "

[2] See *Trans. Inst. Marine Engineers*, 1927-8, p. 366.
[3] See *Bureau of Standard Journals of Research*, November, 1930, p. 985.

is 96 per cent. of its " real " value. With a brass pipe under the same conditions this becomes 93 per cent.

Now a disturbance in the fluid in the pipe, such as a pressure wave caused by the compression stroke of the pump, is propagated through the pipe with the speed of sound, $v_s = \sqrt{K/\rho}$, where K is the bulk modulus of elasticity, and ρ is the density of the fluid. K is thus the bulk modulus of the fluid " in the pipe." Thus, for a fuel oil of specific gravity of 0.86 and K equal to 266,500lb. per sq. in. the speed of sound is 4,800ft. per sec., some hundreds of times that of the actual flow. Such waves may be wholly or partially reflected back at the nozzle, and may again be reflected at the pump end to move again towards the nozzle. During the normal period of injection in a high-speed engine, and with an average length of pipe, such waves may travel several times to and fro through the fluid in the pipe. These pressure waves may appreciably affect the pressure at the nozzle, which, of course, determines the flow from the nozzle, and in an analysis of the injection process they must be taken into account.

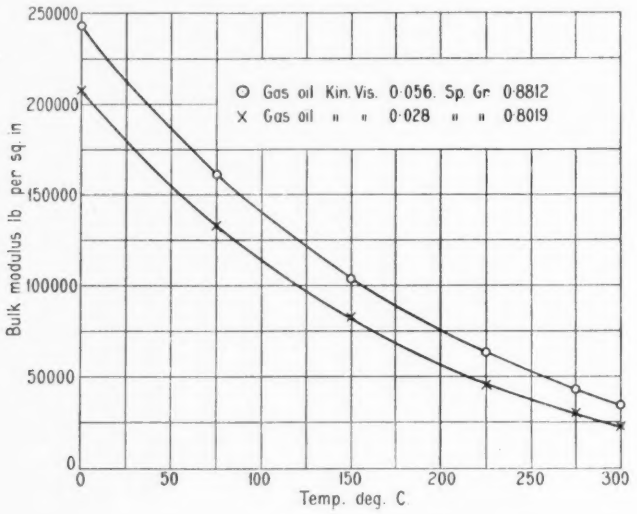

FIG. 3.

Effect of temperature on compressibility—Jessup.

To simplify such an analysis, it will be assumed: (*a*) that the pump plunger is of the same diameter as the pipe, (*b*) that the pump plunger moves with constant velocity, admission and cut-off being port-controlled, with instantaneous beginning and end of delivery, (*c*) that, by virtue of the compressibility of the oil, the fuel next to the plunger is, during the early part of the delivery period, subjected to a high constant acceleration, so that after a small fraction of the delivery stroke this oil is moving with plunger velocity. With these assumptions, a typical case has been worked out using the following data: Bore of pipe, 0.044in.; length of pipe, 23in.; velocity of plunger, 25ft. per sec.; time of delivery period from the pump, 0.004sec.; the bulk modulus of oil " in the pipe," 266,500lb per sq. in.; specific gravity of fuel, 0.86; corresponding speed of sound " in the pipe," 4,800ft. per sec.; pressure in engine cylinder during injection rises from 300 to 800lb. per sq. in.; nozzle of " open " type with an effective area one-fortieth of that of the pipe.

It is shown in Appendix I that, when the fluid at the pump plunger is set in motion, the increase in pressure is directly proportional to the increase in velocity of the fluid. Thus, to accord with assumption (*c*), the front of the pressure wave so set up is a straight line showing uniformly increasing pressure up to a maximum of—

$$P = \frac{\text{Bulk modulus}}{\text{Speed of sound}} (\text{velocity of plunger}) = \frac{266,500}{4,800} .25 = 1,390 \text{lb. per sq. in.} \quad (1)$$

The time for this pressure wave to travel the length of the pipe, 23in., is $\frac{23}{12} \frac{}{4800}$ sec. = 0.0004sec., or one-tenth of the delivery period. Fig. 4 shows, during the complete period of injection, variations of pressure in the

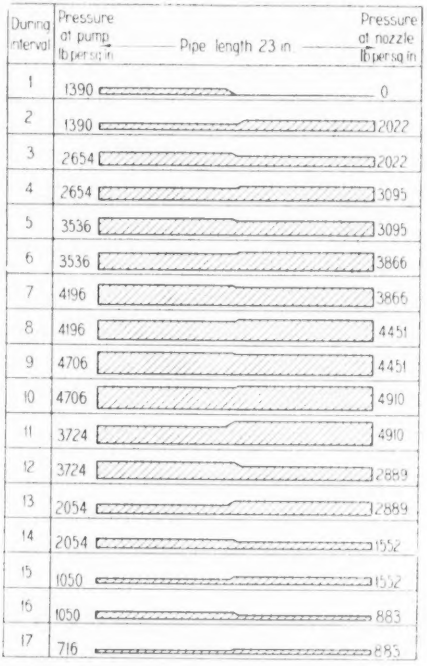

FIG. 4.

Pressures in fuel pipe during injection.

pipe for successive intervals of 0.0004sec. The preliminary period during which the fuel at the plunger acquires the velocity of the plunger is assumed to be short, and this is indicated, in each case, by the short sloping front of the pressure wave. At any instant during interval 1 the pressure at the plunger is 1,390lb. per sq. in. and at the nozzle is zero, the distance the wave-front has travelled being proportional to the fraction of the interval that has elapsed.

At the end of interval 1 the wave reaches the nozzle and injection begins. If the pipe end were closed the pressure wave would be completely reflected; if the nozzle area were equal to the pipe cross-sectional area, there would be no reflection. The actual case is one of partial reflection, the height of the reflected

pressure wave depending on the resistance offered to flow through the nozzle. In the case considered, the initial pressure wave is one of 1,390lb. per sq. in., while the reflected wave is 632lb. per sq. in., giving a total pressure of 2,022lb. per sq. in. With complete reflection this pressure would have been $2 \times 1{,}390$ or 2,780lb. per sq. in., and the difference is accounted for by the velocity of the oil through the nozzle.

The magnitude P_1 of the reflected wave is found thus: The pressure at the nozzle during interval 2 is $(1{,}390 + P_1)$; the cylinder pressure is 300, so that the pressure head, h, across the nozzle is $(1{,}390 + P_1 - 300) \div (\text{density})$. The velocity through the nozzle,

$$V_n = \sqrt{(2gh)} = \sqrt{\left| \frac{2g\,(1{,}390 + P_1 - 300) \,.\, 144}{0.86 \,.\, 62.4} \right|} = 13.15 \sqrt{\ |\ 1{,}390 + P_1 - 300\ |}$$

ft. per sec. The corresponding velocity in the pipe is $V_n/40$. The reflected wave P_1 is due to the reduction of velocity in the pipe from 25ft. per sec. to $V_n/40$. Therefore, from (1),

$$P_1 = \frac{K}{v_5}\left(25 - \frac{V_n}{40}\right) = \frac{266{,}500 \times 25}{4800} - \frac{266{,}500 \,.\, V_n}{4800 \,.\, 40} = 1{,}390 - 1.388\ V_n;$$

i.e., $P_1 = 1{,}390 - 1.388 \,.\, 13.15 \sqrt{(1{,}390 + P_1 - 300)}$, from which $P_1 = 632$lb. per sq. in. V_n may then be calculated directly, giving in this case 547ft. per sec.

The conditions at the nozzle remain constant until this wave, which is completely reflected at the pump plunger at the end of interval 2, again reaches the nozzle at the end of interval 3, when a similar calculation is carried out for the next reflected wave. This process is continued throughout the delivery period of the pump, that is, up to the end of interval 10, during which the pressures at the nozzle and the corresponding velocities are increasing. The pressure in the pipe at the end of any interval may be checked by considering the displacement of the plunger and the outflow through the nozzle up to the instant considered.

At the end of interval 10 the pump plunger stops, in effect, and the wave reaching the plunger at this instant is not reflected. Instead, the oil next to the plunger is brought to rest and a negative wave of 1,186lb. per sq. in., due to the resulting drop in velocity of the oil, travels towards the nozzle. When this reaches the nozzle it is partly reflected, the flow from the nozzle continuing, and the magnitude of the negative pressure wave is calculated in a similar manner to the above. This process continues until the pressure at the nozzle is equal to that in the cylinder. From this point, with the "open" nozzle considered, the oil still under pressure in the pipe expands into the cylinder only as the cylinder pressure falls.

The firm line in Fig. 5 shows the variations in V_n, with this pipe, 23in. long, during the period of injection, plotted on a base of time. Following this line through, it is seen that injection into the cylinder does not begin until the end of interval 1, that is, 0.0004sec. after the beginning of delivery from the pump, an interval termed the "injection lag." This period is, of course, the time taken by a disturbance to travel the length of the pipe.[4] The velocity from the nozzle increases in steps, as shown, reaching a maximum value of 855ft. per sec. The velocity increases with time and, with sufficient time, tends to reach the value corresponding to the plunger velocity, that is, $25 \times 40 = 1{,}000$ft. per sec. After the pump ceases to deliver, the injection continues for a further period of 0.0024sec., the velocity falling off rapidly. Thus, although the pump delivers during 0.004sec., the total time of injection with this pipe is 0.0064sec.

At the end of injection, oil under a pressure equal to that in the cylinder remains in the pipe. As already mentioned, this oil will expand as the cylinder pressure falls. In the present case the fall of pressure is from 716 to 0lb.; the expansion of the oil in the pipe is thus: (716/K . vol. of pipe), giving 0.000094

[4] See Rothrock: N.A.C.A. Technical Note No. 332, for experimental evidence supporting this.

cu. in. The total volume discharged = 0.00182 cu. in., so that, with this pipe, the oil re-expanded is 5.1 per cent. It must, of course, follow that this amount, together with the volume of oil given by the area under the firm line of Fig. 5, is equal to the volume displaced by the pump plunger—shown on the diagram by the chain-dotted line.

Similar calculations have been made for a pipe one-half this length, that is, 11.5in., and the resulting curve of velocity is given as a dotted line in Fig. 5. Comparing this curve with the former, the following points will be noted: The injection lag, 0.0002sec., is one-half of the former value; the velocity increases more rapidly and reaches a higher maximum value of 955ft. per sec.; the total time of injection is 0.004 + 0.0012 = 0.0052sec. Thus, with a shorter pipe, the delivery from the nozzle approaches more nearly that from the pump plunger. The " re-expanded " volume is now 2.5 per cent., or one-half of its former value.

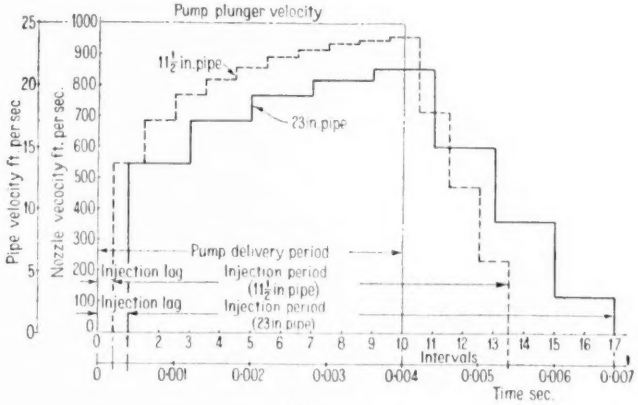

FIG. 5.

Nozzle and pipe velocities during injection—effect of length of pipe.

As regards assumption (*a*), made earlier, that the plunger and pipe have the same diameter, it follows, if continuity of flow be assumed, that this has no effect on the action and, therefore, only simplifies the calculation. The assumption (*b*) of constant pump-plunger velocity is true in some designs; varying plunger velocity will give continuous instead of the stepped curves in Fig. 5, but the case taken is simpler to explain. With regard to assumption (*c*) concerning the setting up of velocity in the oil, some such assumption must be made, and, in any case, the final result is not appreciably affected. The general conclusions reached must, however, be considered in conjunction with the design of particular systems.

Some modification to the forms of the curves will be caused by friction in the pipe, but with the velocities in question the effects upon pressures may be neglected. A further modification is introduced in some designs by the use of a special delivery valve on the pump to obtain a rapid drop of pressure in the piping at the end of delivery from the pump. Such valves, by increasing the volume of oil contained in the pipe, act in a manner opposite to that of the plunger at the beginning of delivery. This sets up a negative pressure wave which travels towards the nozzle, rapidly reducing the existing pressures, with the object of giving a quick cut-off to the injection. Other modifications are necessary when a " closed " spring-loaded injection nozzle is used, more particularly as regards the opening and closing periods.

In this case, during the early part of the delivery from the pump, the pressure waves continue to be completely reflected at the nozzle until the pressure so built up is sufficient to open the injection valve against the spring pressure. From this point onwards the amount of reflection depends on the effective area through the valve, until, with falling pressures, a point is reached when the force exerted by the spring is sufficient to close the valve. The closing of the valve may, under certain circumstances, set up a pressure wave towards the pump. If, on the return of this wave, the pressure at the nozzle is high enough, a re-opening of the valve will take place, giving an undesirable secondary injection. The natural period of vibration of the valve and its spring may also exert an influence in this connection.

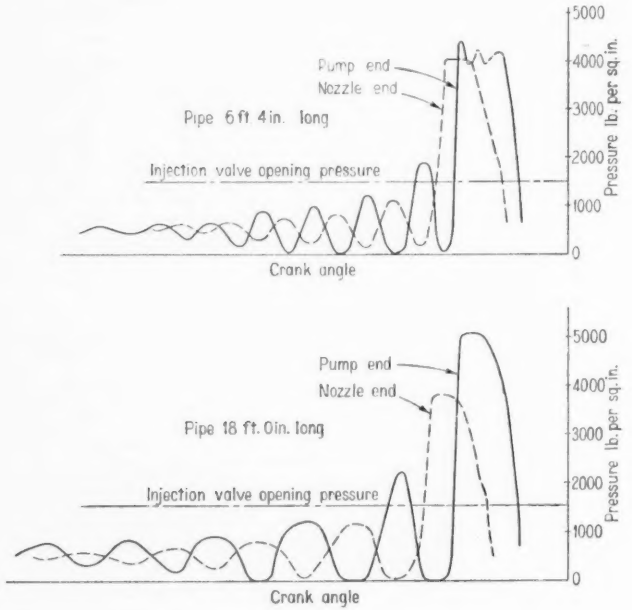

FIG. 6.

Pressures in pipe lines. Effect of length of pipe—E.E.Co.

A number of the foregoing points are illustrated in Fig. 6, taken by the English Electric Co. at their Rugby works, with a Farnboro indicator fitted with a pressure-reduction device. The upper and lower diagrams refer to pipes of different lengths, the firm line showing in each case the pressure variations at the pump end and the dotted line those at the nozzle end. The injection lag is clearly seen and increases with the length of the pipe in the way indicated in Fig. 5. The pressure waves set up after closing the injection valve are very marked, but are not sufficient to cause the valve to re-open, that is, there is no secondary injection. That these pressure waves are damped out very rapidly is clearly to be seen.

This rapid damping of pressure waves, considered with the fact that the natural frequency of the pipes usual in high-speed practice is very high when compared with the engine speeds, would lead to the conclusion that there is little likelihood that waves set up, in any way, by resonance can influence the

injection process. But on this point there is a need for further experimental evidence.

The element of the injection system which determines the final process of injection is the fuel nozzle, the function of which is, broadly, so to sub-divide the liquid fuel and to control its direction of flow into the cylinder that it shall meet the air necessary for its combustion at a suitable rate. The degree of fineness of sub-division and the directions arranged will depend upon the manner in which the mixing of the fuel with the air is to take place, a matter which has been treated in detail elsewhere.[5] It suffices at this stage to say that the form of jet delivered by a nozzle can be finely "atomised," or soft, or less finely atomised, and that the "penetration" of the jet, under a particular pressure at the nozzle, is less, the more finely the fuel is atomised. Good penetration and fine atomisation can thus only be obtained simultaneously by extremely high injection pressures. Given the desired pressures at the nozzle, the rate of injection of the fuel is naturally determined by the effective areas of the orifices, through which the oil passes at successive instants during the injection process. So that the design of a fuel nozzle consists in suitably arranging the forms and effective areas of these orifices.

By far the majority of fuel nozzles on high-speed engines are either of the "open" type or of the spring-loaded automatic valve type. As regards "open" nozzles, it is shown in Fig. 5 that the period and the rate of injection are controlled by (*a*) the velocities of the pump plunger during its delivery period, and (*b*) the length of the pipe. It follows from the reasoning upon which this figure is based—remembering that the pressures in the piping depend not only upon the pump motion but also upon the proportion of fuel passing at any instant through the nozzle—that the ratio of the effective area through the nozzle to the cross-section of the pipe is a further factor; the smaller the nozzle, the higher is the pressure in the piping and the longer is the period of fuel injection. The advantage of the open type of nozzle is its simplicity; its drawback is the relative lack of control over the injection after the pump has ceased delivery, with the possibility of dribbling as the velocities through the nozzle fall off. Against this drawback the spring-loaded nozzle offers distinctly better possibilities.

These possibilities follow from the introduction of two further means of controlling the injection: the strength of spring acting on the valve at the nozzle may be set to open at any desired pressure; by employing a valve of suitable shape, the effective areas of cross-section through the valve at various valve lifts can be given any desired values. By correlating the velocities at the pump and the pressures at the nozzle with these areas, the rates of injection can be controlled as desired over the whole period of injection. There is, perhaps, one further point that should be mentioned. The fuel pressure acting to open the valve against the spring pressure does not act on the area of the valve within the outside circumference of the seating; this area is subjected only to the pressure existing in the engine cylinder. Once the valve is open, however, and flow is taking place, the whole area is exposed to the fluid pressure. So that the fluid pressure at closing is actually lower than at the instant of opening the valve, depending upon the difference of these areas.

Processes Within the Cylinder.—Mixing, Ignition, and Combustion

It must be admitted that the correlation of the injection process with the processes within the cylinder remains to-day one of direct experiment in each individual case. The variables controlling the mixing alone are too complex for the general conclusion from experiments apart from an engine to be applied directly to a practical design. Such experiments do, however, indicate ways in which the mixing may be regarded, grouped as they are under: (*a*) hydraulics experiments, dealing with the discharge conditions which control the quantity

[5] See *Engineering*, loc. cit.

discharged, the penetration, and the divergence of sprays, and (*b*) dynamic experiments, exploring the momentum of sprays under varying conditions of atomisation, divergence and penetration. When conclusions have been reached under these headings, however, there is still the influence which combustion itself may exert upon the distribution of the fuel in the combustion air; so that, at present, every new engine constitutes a new experiment in this connection.

Although the results of experiments away from the engine are not suitable for unqualified application in design, this it not to say that the work already done is not of value. On the contrary, such work is extremely valuable, but has not yet gone far enough, largely on account of its inherent difficulty, and all possible support should be given to further investigations of this nature. In the present paper, which deals more particularly with engine conditions, it is only possible to make brief reference to these fields of work, but the relevant publications are given in Appendix II.

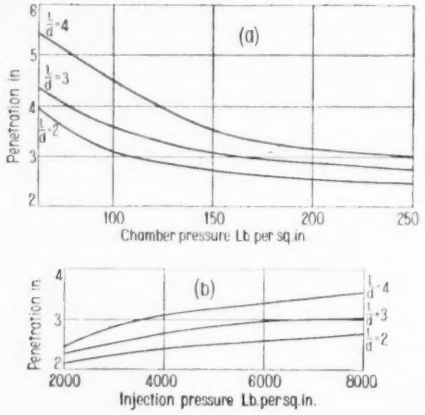

FIG. 7.

Penetration results with different value of length/diameter of orifice—N.A.C.A.

The work of A. L. Bird at Cambridge in connection with the coefficients of discharge of nozzles and the ignition of fuel jets is too well known in this country to need special mention here. Apart from Bird's work, lengthy investigations of the hydraulics and dynamics of injection have been carried out in America under the National Advisory Committee for Aeronautics by Joachim, Beardsley and others. Fig. 7 may be regarded as summarising their work on penetration under various conditions, and gives the results that are probably of most direct value for engine design. Other similar investigations have been made at the Pennsylvania State College by De Juhasz and Schweitzer. But, while awaiting complete scientific data, it is certain that much may be learned by considering closely the processes in actual engines of various types of design, and by correlating the results.

The importance of indicator diagrams as an aid to the study of these processes hardly needs to be emphasised, and, for high-speed engines, diagrams showing variations of pressure obtained directly upon a crank-angle or time base by means of indicators of the Farnboro type are invaluable. Such diagrams give at once the characteristics of an engine under the prevailing conditions of speed, load, and fuel, and it is mainly by considering the circumstances influencing the forms of these diagrams that progress can be expected. These circumstances,

as will be seen later, depend upon two distinct things, namely, the design of the engine and the physico-chemical characteristics of the fuel used.

Fig. 8 shows a typical form of diagram, and to facilitate consideration of the conditions governing ignition and combustion, this curve of pressure, on a time base, is divided into the parts AB, BC, CD and DE.[6] AB and BC form one continuous curve, following the normal compression curve from the engine. B marks the point at which the injection of the fuel into the cylinder begins, but it is found that no increase of pressure, above that due to compression alone, occurs until the point C is reached where the departure from the dotted compression curve is seen. Between B and C part or all of the fuel has been injected, but ignition does not begin until C, when combustion causes the much more abrupt rise of pressure shown in the figure from C to D, D being the point of maximum pressure. From D onwards the pressures in the cylinder are governed primarily by the changes in volume following the out-

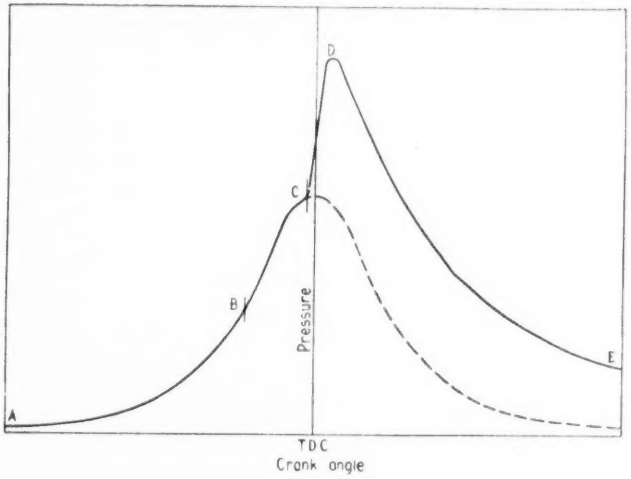

FIG. 8.

Typical indicator diagram.

ward movement of the piston, and also by the combustion of the fuel not burnt at D. Of the curve ABCDE, the parts BC and CD are of outstanding importance.

The interval of time from B to C, during which fuel is present in the cylinder but has not yet commenced to burn, or, more exactly perhaps, has not yet caused an increase of pressure above that due to compression, is best described as the "ignition lag."[7] Between C and D combustion is rapid, the rate at which the chemical energy of the fuel is being changed to pressure energy being given by the slope of CD. In general, the changes of volume between C and D are very slight, since the piston is near or at inner dead-centre; the rate of rise of pressure from C to D is therefore dependent only upon the rate of burning of the fuel.

Now in considering the desirable form of the curve ABCDE, there are certain opposing conditions to satisfy. On the one hand, for maximum theoretical

[6] Such a sub-division is, of course, by no means new, but something of the kind is essential in a study of the processes. *Cf.*, for instance, Ricardo: *Proc. I.A.E.*, Vol. XXIV., p. 649.

[7] This has been called the "delay period" by Ricardo and others, but in view of the other delay period, called earlier the "injection lag," it is desirable to have a separate term here.

efficiency, combustion should take place at constant volume at inner dead-centre, that is to say, CD should be vertical; the output then depends on the height of D, the maximum pressure. On the other hand, early and very high values of maximum pressure increase the losses to the walls at and near inner dead-centre, and bring down the thermal efficiency. Also, and what is more important, a high rate of pressure-rise will cause the running of the engine to be " rough," and will increase the loads on the working parts. So that, as a practical compromise, the slope of CD must not be too steep, and the maximum pressure should be reached shortly after dead-centre, when its value will be lower. Of all the factors influencing the performance of high-speed oil engines, ignition lag and rate of pressure-rise are the most important.

It is interesting to note that ignition lag was first observed on an engine by Professor Hawkes.[8] He was then led to carry out a series of experiments to determine the conditions governing the ignition lag (or, as he called it, the " time lag ") of shale oil under pressures and temperatures of the order of those met with in the engine. In the experiments the oil was injected axially into a cylinder of compressed air at the desired pressure and temperature. The results are shown in Fig. 9, and the sensitiveness of the ignition lag at low tem-

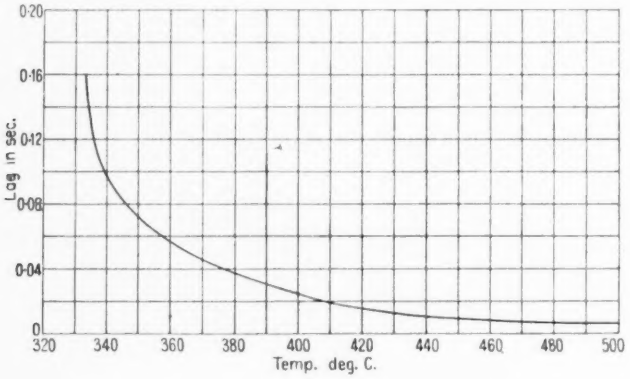

FIG. 9.

Ignition lag of shale oil—Prof. Hawkes.

peratures to changes of temperature is clearly seen. He found that the lowest temperature at which ignition occurred was 260°C., the corresponding value of the ignition lag being 3·5sec., and that the results showed little difference with various pressures of the air from 200 to 400lb per sq. in., and with injection pressures from 2,000 to 4,000lb. per sq. in.

Further experiments upon ignition lag were subsequently carried out by A. L. Bird[9] at Cambridge and by Professor Neumann[10] at Hanover, both using apparatus similar to that of Hawkes. They both saw that, in addition to temperature, the density, rather than the pressure, of the medium into which injection took place was also an important variable. Bird's results are given in a three-dimensioned form in Fig. 10, ignition lag, in seconds, being plotted vertically, while air temperature is plotted along one horizontal axis, and p/T, proportional to air density, along the other. This diagram is interesting, since it gives a

[8] See *Trans. N.E. Coast Inst. of Engineers and Shipbuilders,* Vol. XXXVII., 1920-1, p. 37.
[9] See *Proc. I.Mech.E.,* 1926, p. 955.
[10] See *Zeitschrift des Ver. Deutscher Ingenieure,* 1926, Vol. 70, p. 1071.

picture of the kind of relationship existing between ignition lag and the temperature and density of the air. But, as in Hawkes's tests, the air at injection was at rest, and the values of ignition lag are much too high to be correlated with those observed in actual engines.

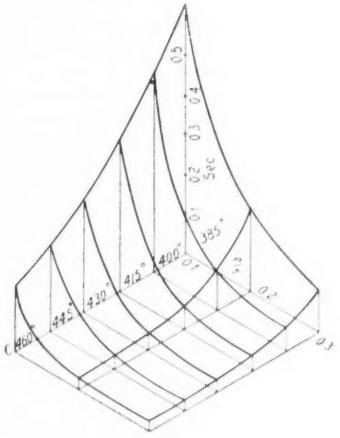

FIG. 10.

Ignition lag—Bird.

Neumann used a fan in his vessel and measured the ignition lag with and without swirling of the air. His results are shown, for a pressure of 114lb. per sq. in., in Fig. 11, ignition lag being plotted on temperature as base. Curve

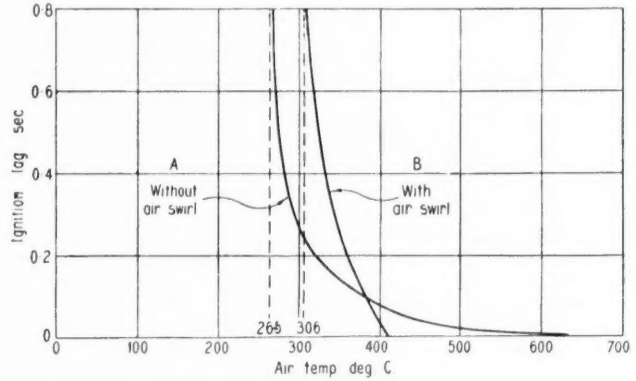

FIG. 11.

Ignition lag—Neumann.

A was obtained with the air at rest, the lowest temperature at which ignition took place then being 265°C., curve B was obtained with swirling of the air, the lowest ignition temperature being 306°C. Although the type of swirl set up probably bears little resemblance to that prevailing in the cylinder of a high-speed engine, its effects upon ignition lag are very definite.

It is desirable at this point to try to estimate the character of the " reactions " taking place during the ignition lag. Before ignition can be initiated it is obvious that the hydrocarbons in the fuel must be in a suitable state, whatever that may be, for the chemical reactions to begin and to continue sufficiently rapidly. It may be emphasised, too, that from the point of view of oil-engine operation at high speeds the time intervals available are extremely short, and that although the speeds of revolution are at present generally lower than in the petrol engine, the processes in the cylinder of the oil engine are more complex than those in the cylinder of the petrol engine. In the latter, the greater part of the fuel is, at the instant of ignition, in a gaseous state, *i.e.*, in the same physical state as the combustion air; in the former, on the other hand, liquid fuel at ordinary temperatures is being sprayed into air at the much higher compression temperatures. It is thus obvious that the droplets of fuel must undergo a considerable increase of temperature before combustion can begin, and must, therefore, in the short time available, take up heat rapidly from the high-temperature air. What is not so clear, however, is the nature of the physical changes in the fuel before and during the chemical combination of combustion, and it is desirable to consider the diverse theories advanced on this question.

It is thought by many that the droplets of fuel must be completely vaporised before ignition can begin, combustion then taking place as in the petrol engine. Chemical reactions are most rapid when the proportions of fuel and air are " correct," and it is considered that the unvaporised part of each droplet is surrounded by mixtures of air and vaporised fuel in zones of decreasing richness. So that the droplet, in its passage through the air, is steadily diminishing as it vaporises, until it is completely vaporised and burnt. Evidence of a two-fold nature, however, contradicts this view of the combustion process. In the first place Neumann has calculated the rate at which such a liquid droplet can take up heat, and, with the known values of the latent heats of evaporation and conductivities in the liquid, has found that, in the time available, not more than five per cent. of the volume of the droplet can be vaporised, even when the air is given a swirling motion. In the second place there is the fact that if vaporisation were the controlling factor, then those fuels which are most easily vaporised would behave best in the engine, but the contrary is the case. Actually, the ignition points of some gas oils are lower than their mean boiling points, so that with these fuels, which behave quite satisfactorily in the engine, complete vaporisation before ignition is impossible. So that, since vaporisation *alone* is limited to a small fraction of the fuel, the complete process of combustion, as distinct from its initiation, cannot follow from complete vaporisation.[11]

An alternative view is that for ready ignition of the fuel particles a cracking of the oil into its lighter hydrocarbon fractions must take place. This condition when examined, however, is found not to hold, since fuels which behave most satisfactorily in the engine show small tendency to crack, while other fuels which show the greatest tendency to crack are quite unsatisfactory as regards engine performance. There is the fact, too, that the ignition temperatures of the cracked fractions are not lower, but actually much higher, than those of the uncracked fuels. Moreover, whereas the ignition temperatures of oils from various sources are sufficiently different to be consistent with their differences of performance in the engine, the ignition temperatures of all the cracked fractions of these lie within a restricted range. Thus, the direct cracking of the fuel, so far from being an essential condition of the combustion, is, on account of the higher ignition temperatures, actually to be avoided in the engine.

Before dismissing the vaporisation and cracking conditions altogether, however, there is one point to bear in mind. Measurements of the various physical constants of the fuel, *e.g.*, the ignition and boiling points, have been made under

[11] It would thus seem that the importance of the distillation curve of fuel oil has been exaggerated.

" static " conditions; the operations in the engine would take place under rapidly changing conditions, and it is suggested that the static values are, in consequence, not applicable to the engine operations. But there is little in general experience in support of this view, and further theories to explain the process of combustion must be sought.

The following appears the best explanation in the light of present knowledge, and must be accepted in that sense.[12] The oil droplets receive heat from the air during the interval of the ignition lag, and their surface temperature is raised towards that of their ignition point. Oxygen then combines with some of the surface hydrocarbon molecules to form unstable peroxides; these are immediately decomposed, with the evolution of such large amounts of heat that the ignition of the neighbouring hydrocarbon molecules is thus initiated; combustion proceeds subsequently with the rapidity corresponding to these high temperatures. Thus the interval of time up to the initiation of burning, *i.e.*, the ignition lag, is occupied mainly by the heating of the surface of the droplets, the ignition itself being of extremely short duration.

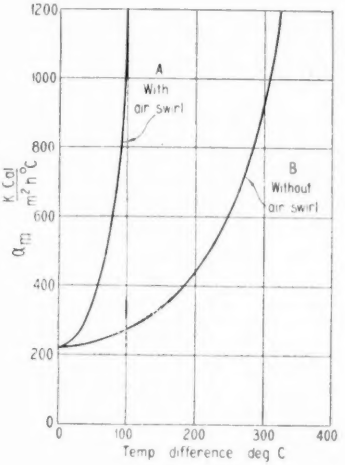

FIG. 12.

Heat transfer from air to fuel—Neumann.

If this explanation of ignition lag be accepted, then the chief factor would appear to be the rate of heat transfer from the air to the droplets of oil. This question of heat transfer has also been considered by Neumann,[13] and his calculations are both interesting and illuminating. Working back from the quantity of heat necessary to raise unit weight of fuel to the ignition temperature, and using the observed values of ignition lag of Fig. 11, he calculated the mean coefficients of heat transfer, α_m; these are plotted in Fig. 12 on a base of the difference between the air temperature and the ignition temperature. Now, the values on this curve are of the order of one hundred times the normal values for heat transfer from air to ordinary bodies, a fact which leads to the conclusion that chemical reactions, in addition to the mere transfer of heat, must be present.

[12] *Cf.* Discussion on Joachim's paper: American Soc. Mech.. Engineers, O.G.P. 51-11, 1929, p. 99.
Sass: *Kompressorlose Dieselmotoren,* p. 30.
[13] Neumann: *loc. cit.*

This conclusion is supported by the extremely rapid rise of a_m with the air temperature, which is, of course, consistent with the direct dependence of the speed of chemical reaction upon temperature.

Without specifying the nature of the chemical reactions, these results would seem to indicate that, as seen earlier, evaporation plays at most a minor part in the process; the rate at which heat can be transferred from the air to the oil is the dominant condition. Heat transfer depends upon the difference of temperature between air and fuel, and upon the relative motion of the air and fuel, and if the rate of ordinary heat transfer is increased, then the speeds with which these chemical reactions take place will be proportionately much higher. The latter take place more rapidly, also, the higher the density of the air, a circumstance which explains the lower values of ignition lag in high-compression engines when compared with those with lower compression pressures.

Neumann applied this reasoning to the indicator cards obtained from three engines of quite different design, as given in Fig. 13 (*a*), (*b*), and (*c*). The engines in question were not actually high-speed engines, but in view of the value of these calculations as illustrations of what is most probably taking place in high-speed engines of similar design, they well repay study.

The top diagram was taken from a Deutz direct-injection engine in which the combustion chamber was roughly hemispherical, the injection nozzle being placed on the cylinder axis. The middle diagram belongs to a Junkers opposed-piston engine, in which, it will be remembered, the air has a rotational swirl about the cylinder axis, and injection takes place diametrically. The bottom diagram is from a Körting ante-chamber engine with combustion chamber of the form shown. The injection nozzle is carried well down into the water-cooled ante-chamber, so that its distance from the upper end of the water-cooled passage connecting the ante-chamber and the cylinder is small. The fuel is injected as a narrow stream directly on to the walls of this passage. During injection the air compressed behind the piston is continuing to flow at high velocity through the passage into the ante-chamber, meeting the injected fuel in the passage. Ignition begins in the ante-chamber, and the consequent rise of pressure forces the remaining unburnt fuel, for which, of course, there is not sufficient air in the ante-chamber, into the main combustion chamber, where combustion is completed. For each of the three engines the curves shown in Fig. 13 were determined.

The bold black lines are the indicator cards, on crank-angle as base; the two dotted lines on each diagram show respectively the rise of temperature and the increase of density of the air during the compression stroke; the thin, firm lines show the ignition points calculated for the fuel under the conditions of pressure and air temperature, as these change progressively during the compression stroke. The lines BB on each diagram show the points at which fuel begins to be delivered from the pump; the lines CC show the points at which ignition begins. The crank-angles passed through between these pairs of lines give, unfortunately, (ignition lag)+(injection lag) instead of the ignition lag alone, but, at the slow speeds of running of these engines—about 300 revs. per minute—the difference is probably not important, and, in any case, does not affect appreciably the authors' subsequent conclusions. The lengths of the parts of the ordinates intercepted by the shaded areas give the differences between the air temperature and the ignition point of the fuel during the ignition lag. As pointed out by Neumann, the differences in the forms of these shaded areas are consistent with the differences in the working processes occurring in the three engines.

These diagrams, however, upon further consideration, throw a light upon other important questions. The brake thermal efficiency of all three engines is of the order of 36 per cent. The Junkers and Deutz engines are directly comparable on the basis of cylinder output and speed of revolution; the Körting engine runs more slowly and develops about three times the power per cylinder,

so that it is relatively more favourable towards a high efficiency. Leaving these differences out of account, however, it is seen that the ignition lags and the shaded portions of the Junkers and Körting diagrams are similar. In both engines a considerable relative motion between fuel and air and good atomisation are present, conditions favourable to a rapid interchange of heat from air to fuel; in the Junkers engine there is set up a vigorous rotational swirl across which the finely divided particles of fuel are injected; in the Körting engine the contrary flow of fuel and air in the passage will tend towards the same favourable condi-

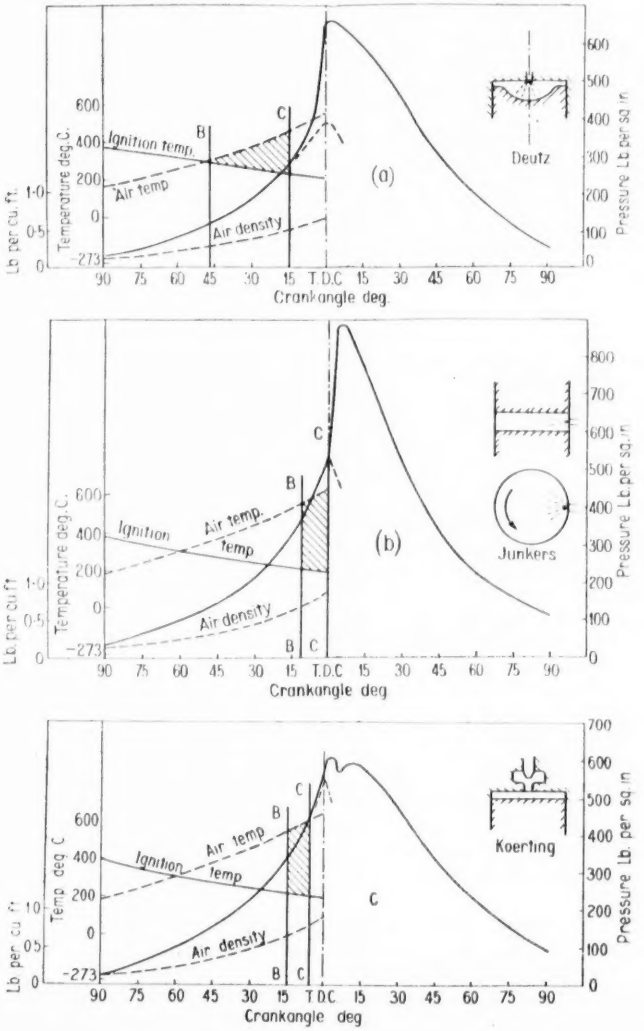

FIG. 13.

Cylinder conditions during compression stroke—Neumann.

tions during the ignition and early stages of burning. That the later stages of burning are much more rapid in the Junkers engine than in the Körting is seen by the relative rates of rise of pressure and by the respective maximum pressures. In the Deutz engine the fuel must penetrate a considerable distance into the air, and to do this it cannot be so finely atomised; further, there is no definite motion given to the air to assist the mixing. Both circumstances tend towards less rapid interchange of heat and lead to the high value of the ignition lag and the necessarily early injection of the fuel; so that, as the figure shows, injection takes place under conditions of air temperature unfavourable to rapid interchange of heat. Once ignition has begun, however, the Deutz engine shows a similar rapid rise of pressure to the Junkers engine.

These differences between the forms of the diagrams thus concern (*a*) ignition lag, and (*b*) the subsequent rate of rise of pressure and its later variation. Under (*a*) it is seen that a low value of the ignition lag is brought about essentially by making possible a rapid transfer of heat from the air to the fuel—the direct consequence of a rapid rise of temperature of the fuel is that any chemical reactions are speeded up at a relatively still greater rate. This rapid transfer of heat can be facilitated as follows: First, by fine atomisation of the fuel by which the surface/volume ratio of the droplets is increased; secondly, by a vigorous relative motion of the fuel and air, and, thirdly, by directly increasing the density and temperature of the air towards the end of the compression stroke by raising the compression ratio.

As regards (*b*), it is seen that after ignition has been initiated the subsequent rates of rise of pressure and the values of the maximum pressures attained are very different in the three engines. In the Junkers engine, with its definite and vigorous rotational swirl, after the small ignition lag, the combustion once begun continues to be very rapid, and leads, after a very rapid rise of pressure, to a high maximum pressure shortly after the dead centre. In the Deutz engine the subsequent combustion is similarly rapid. In both engines the combustion chamber is compact in form, and whereas in the Junkers engine the definite swirling will assist the uniform distribution of the fuel in the air, in the Deutz engine, in the absence of definite swirling, the good directional distribution is probably further helped by the lengthy ignition lag. With the Körting engine, on the other hand, although the lag is short, as in the Junkers engine, the subsequent combustion is relatively very slow, with a low maximum pressure and a real approach to a constant-pressure cycle, which would lead, if the other conditions of size and speed did not outweigh it, to a lower thermal efficiency.

These results lead to the following conclusions: A short ignition lag may be associated in engines of different design either with a high or with a low rate of pressure-rise; a high rate of pressure-rise may follow, with different engines, either a long or a short ignition lag. It would thus be dangerous to apply conclusions concerning ignition lag and rate of pressure-rise, drawn from any one engine, to another engine in which the processes of injection and distribution of the fuel are not exactly similar. Differences may also be found in the behaviour of cylinders of similar design but of different sizes, as, for example, in a range of engines from the same builder. So that each separate type of design is governed by laws which must be independently determined and not inferred from other designs.

For instance, with some engines, ignition lag may be constant in time and independent of engine speed, *i.e.*, the crank-angle turned through during the lag is directly proportional to the speed. It must be clear, however, from what has been said concerning the effect of heat transfer from air to fuel upon lag, that the speed of the engine, in so far as it influences this rate of heat transfer, must influence also the duration of the lag. The influence of speed upon the rate of heat transfer will obviously vary with the design of the engine and, in particular, with the method of bringing the air and fuel into combination—that is, whether

the engine follows a " direct-injection " method, with or without definite swirling, one of the " ante-chamber " methods, or the " auxiliary air chamber " method. It follows that the engine in which the rate of heat transfer is increased directly with the speed of revolution will tend to have the same ignition lag, based on crank-angle, at all speeds. In other words, as regards ignition, such an engine will be very flexible as regards speed.

The authors have examined indicator diagrams, kindly supplied by the Associated Equipment Company, taken with a Farnboro indicator on the company's single-cylinder Acro unit. In these tests the quantity of fuel injected per cycle was constant over a speed range from 500 to 2,000 revs. per minute, the brake mean effective pressure being of the order of 80lb. per sq. in. Ignition lag in terms both of crank-angle and time is shown in Table 1.

TABLE 1.

Speed, r.p.m. ...	500	750	1,000	1,250	1,500	1,750	2,000
Ignition lag, crank-angle deg. ...	5	14	14	11	13	11	11
Ignition lag, time sec.	0.0017	0.0032	0.0024	0.0015	0.0015	0.0011	0.0009

While the process of combustion in this " auxiliary air chamber " engine is by no means clear, these figures are convincing as showing how the engine speed affects ignition lag in this design.

A further interesting point concerning the ignition lag with this engine was noticed on examining the results from a series of tests at a constant speed of 1,000 revs. per minute, with brake mean effective pressures ranging from " no load " to 83.5lb. per sq. in. The ignition advance was varied from 22 degrees at no load up to 28 degrees, but the ignition lag was found to be sensibly constant. This is, however, consistent with the mode of operation of the fuel pump, in which the cut-off determines the quantity of fuel injected, the rate up to the points of cut-off being constant at constant speed.

In connection with the processes within the cylinder, it is now possible, in the light of the foregoing considerations, to make certain inferences concerning the desirable form of indicator diagram. Referring to Fig. 14, it may be said that

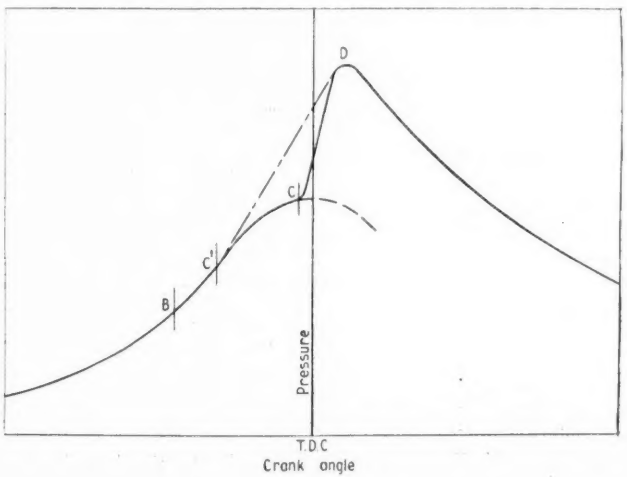

FIG. 14.

Effect of reduced ignition lag.

the position of points D and B are relatively fixed: the maximum pressure at D is limited, in a particular design, by questions of strength, and its position with respect to inner dead-centre by the question of thermal efficiency; the "earliness" of B is limited by the rate of heat transfer from air to fuel possible with a particular design. So that, the maximum interval from B to D being limited, the problem is to make the best possible use of this interval.

This interval is made up of BC, the ignition lag, and CD. Thus, by reducing the ignition lag, as from BC to BC', the interval available for the rise of pressure to D is increased, and the mean slope, showing the mean rate of pressure-rise, decreased from the firm line CD to the broken line C'D. This change will, at the expense of a slight increase of negative work during the compression stroke, lead to greatly improved smoothness of running and general reliability. To this end, therefore, a reduction of ignition lag, and a suitable control over combustion conditions, to give the curve BC'D, should be the objectives of further development work.

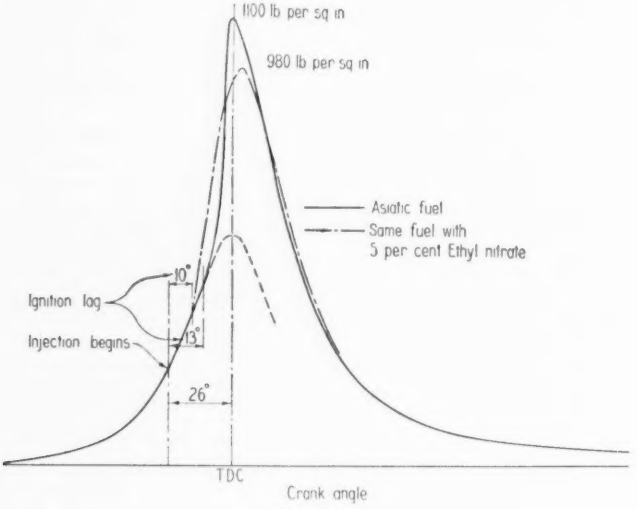

FIG. 15.

Effect of ethyl nitrate on combustion—A.E.Co.

In addition to the influence, already discussed, of engine design upon ignition lag, there remains the behaviour of engines with different fuels. Here, again, generalisations from any particular type of design may prove misleading, and systematic and correlated investigation is necessary. It is general knowledge that fuels from different sources behave differently in any particular engine, both as regards ignition lag and smoothness of running, but little is known of the circumstances determining this behaviour. "Pro-detonating dopes" or "ignition accelerators" have been proposed for the reduction of ignition lag. H. R. Ricardo has found,[14] for instance, that small quantities of amyl nitrate are beneficial in this respect. Ethyl nitrate is another substance of which the influence is similarly beneficial.

Fig. 15 shows two indicator diagrams, supplied by the Associated Equipment Company, from their Acro engine, taken at a speed of 1,000 revs. per minute,

[14] Ricardo: *loc. cit.*

both with the same brake mean effective pressure of 83.5lb. per sq. in. The firm line diagram was obtained with an Asiatic fuel as delivered; the broken line diagram was obtained with the same fuel to which 5 per cent. of ethyl nitrate had been added. The improvement in the performance, both as regards the reduction in the maximum pressure and in the rate of pressure-rise is striking; this was naturally borne out by the much more satisfactory running observed with the doped fuel. But, it may again be emphasised, it would be unwise to infer similar performances with these two fuels on an engine of different design.

To summarise, it would appear that a short ignition lag and a satisfactory rate of pressure-rise may be attained by speeding up the chemical reactions prior to ignition. It has been shown that engine design may, by facilitating the transfer of heat from air to fuel, have this desired effect; further, evidence has been submitted showing that the composition of the fuel itself has an important bearing on its behaviour in an engine, which leads to the conclusion that the speed of chemical reaction is affected. So that, in addition to a better understanding of engine design, an improved knowledge of fuels would widen the range of sources from which fuels may be drawn, since fuels at present unsatisfactory might, with the addition of other substances, be rendered suitable for use in high-speed engines.

Conclusion

The authors have elsewhere compared the present state of development of the high-speed heavy-oil engine, particularly in its diversity of form, to that of the petrol engine of twenty-five years ago. In the interval the petrol engine has reached a more or less standard form, and a vast volume of experience has been gained. Successful competition by the heavy-oil engine will, therefore, only be possible by careful investigation of all matters affecting its performance. The following are suggested as points upon which fuller knowledge is urgently needed:

(1) Ignition lag, and how this is influenced (*a*) by rate of fuel injection, *i.e.*, by the fuel pumps, nozzles and systems, (*b*) by regulated movement of the air, (*c*) by cylinder design, (*d*) by various fuels.

(2) Fuels and their physical characteristics; namely, data of a similar nature to those concerning petrol engine fuels made available by the work of Ricardo, Tizard, Pye, and others.

Especially under (1) is co-operative action essential. In view of the extremely valuable results obtained by the Marine Oil Engine Trials Committee, the authors would suggest similar co-operation, through the technical Institutions, by the firms producing high-speed heavy-oil engines.

Finally, the authors would express their best thanks to those firms mentioned in the text who have so willingly placed information at their disposal.

Appendix I.

It is necessary to show that when a change takes place in the velocity of the oil at the plunger, the induced pressure is directly proportional only to that change of velocity.

On any velocity-time curve, such as that in Fig. 16 (*a*), take an elemental strip as shown. Consider only the change due to this change of velocity δv in the small interval of time δt, assuming, at first, constant conditions before and after the interval, as indicated by the dotted lines. This change of velocity must be caused by a change of pressure, δP, say. So that a pressure wave of magnitude δP will travel with the speed of sound along the pipe.

Fig. 16 (*b*) shows the curve of pressure after a finite time, t, from the beginning of the disturbance. P is the pressure in the fluid due to any previous velocity, v, at the pump and δP is the rise of pressure due to the increase δv.

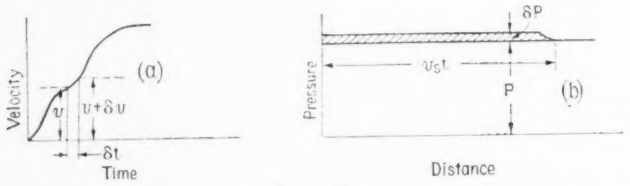

FIG. 16.

In the limit, the shaded area becomes a rectangle. In this interval of time the wave due to the disturbance has travelled a distance $v_s \cdot t$, and the volume of fuel affected is $\frac{\pi d^2}{4} \cdot v_s \cdot t$.

The additional pressure acting on this volume is δP. The decrease of volume of the oil in time t due to the increase of velocity δv is $\delta v \cdot t \cdot \frac{\pi d^2}{4}$.

$$\text{The Strain} = \frac{\text{Decrease of volume}}{\text{Original volume}} = \frac{\delta v \cdot t \cdot \frac{\pi d^2}{4}}{v_s \cdot t \cdot \frac{\pi d^2}{4}} = \frac{\delta v}{v_s}.$$

$$\frac{\text{Stress}}{\text{Strain}} = K, \text{ the bulk modulus of elasticity.}$$

Thus, $\frac{\delta P}{\delta v / v_s} = K$, and, therefore, $\delta P = \frac{K}{v_s} \cdot \delta v = \text{Constant} \cdot \delta v$, *i.e.*, the change of pressure is directly proportional to the change of velocity.

It follows, therefore, that the pressure/time curve of the fluid at the pump plunger is of the same form as the velocity/time curve shown in Fig. 16 (*a*), the form being unspecified. The pressure distribution of the front of the wave is thus determined from the velocity/time curve of the oil at the pump plunger.

APPENDIX II.

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Discussion

Dr. W. R. Ormandy (representing the Chemical Engineering Group), in opening the discussion, said: As a member of the Councils of a number of Institutions which are necessarily interested in the subject of the paper, I have been urging for years the need for joint meetings. It seems such a shame and so uneconomic that when a distinguished man is prepared to give a paper embodying the result of original work which would be of interest to many branches of the scientific world, he should only be able to give it before some comparatively small Institution. Such a meeting as this, with a packed audience, provides the solution.

The authors have dealt at some length with the properties of fuels, and in view of the cry that is arising at the present time for the development and use of home produced fuels, that is, oils produced from coal, it is interesting to note that for compression-ignition engine purposes one of the characteristic properties of oil produced by the distillation of coal is that of high spontaneous-ignition temperature. This is exactly what the compression-ignition engine designer does not need, but, on the other hand, it is exactly the property which the high-speed petrol engine designer requires in his fuels.

The authors have rightly attached a lot of importance to the subject of time lag in its relation to compression-ignition engine running, and have pointed out the value of turbulence in reducing this lag. Some experimental work carried out in my laboratory on spontaneous-ignition temperatures has a bearing on this point. If into a hollow crucible contained in a block of steel capable of being heated to a known temperature a current of oxygen be led and heated to the temperature of the block, and into this hot oxygen atmosphere a drop of fuel be allowed to fall, a number of interesting circumstances arise. With a heavy mineral oil, for example, there will be a temperature at which nothing will apparently happen, but at one or two degrees C. higher there will be an instantaneous explosion, whilst in between these temperatures there will be one at which the explosion follows some 20 seconds after the drop of fuel has fallen. It appeared interesting to find out what was happening during this period of 20 seconds, and experiments were made to study this point. A hair-fine thermo-couple, attached to a delicate galvanometer, was inserted in the crucible, and the galvanometer caused to record on a revolving drum covered with photographic paper. With this arrangement it was possible to note what temperature changes took place in the crucible during the period which elapsed from the entry of the drop to the period of the explosion, or the period immediately after the introduction of the drop when an explosion did not take place. These results are clearly shown on the three curves in Fig. 17.

Curve No. 1 was carried out at a temperature of 241°C., being 4.5 degrees below the spontaneous-ignition temperature, from which we may gather that the entry of the drop lowers the temperature momentarily, and that thereafter no action takes place productive of heat evolution.

Curve No. 2, carried out at 245°C., shows the same drop in temperature as the fuel enters, but there is subsequent considerable increase of temperature, which rises to a maximum 27 seconds after entry of the drop and ceases 70 seconds after its entry. This increase in temperature amounts to 7 degrees C. and is obviously explained by the assumption that a flameless combustion is taking place during this period, but that the rate of heat evolution is not great enough to bring about an explosion. This period of flameless combustion lies between the points A and B on Curve No. 3, taking place at a temperature of 245·5°C. It will be seen that the points A and B are now much closer together, occupying a period of 9 seconds, whereafter the temperature rise becomes vertical and explosion takes place.

It is interesting to note what a small difference suffices to bring about great changes in respect of ignition. It may, I think, be assumed that during the period A and B turbulence or agitation would be of no assistance, though from the point B onwards in the cases where explosion eventually takes place agitation or turbulence is undoubtedly of the greatest value.[15]

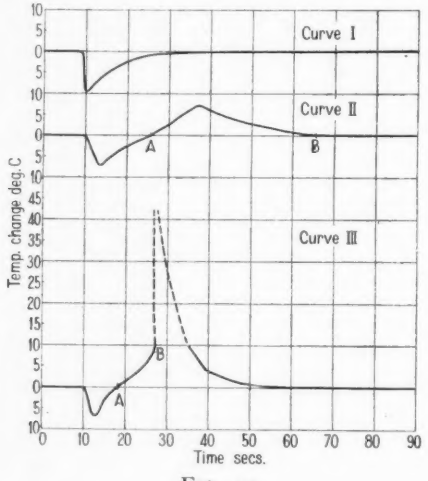

FIG. 17.

If a variable-compression compression-ignition engine were available somewhat similar in principle to the Ricardo variable-compression petrol engine, it would be exceedingly interesting to drive such an engine at a compression just low enough to prevent spontaneous ignition and to analyse the effluent gases. These gases would be the production of the flameless combustion period and, judging by the work of Bone and others, might be expected to be complex in character. On passing oxygen together with heptane over iron heated to just below the spontaneous-ignition temperature, the only product of combustion which we could find was carbon-dioxide, from which it would appear as though even at those low temperatures complete combustion was arrived at, but the whole of this work is well worthy of further study.

Mr. ALAN E. L. CHORLTON (representing the Institution of Mechanical Engineers and the Institute of Marine Engineers): The paper is excellent in that it compares current research on certain oil engine problems and is not a paper written solely about the work of one man. It begins with a comparison of the

[15] For further details see *Jour. I.Pet.Tech.*, Vol. X., No. 43, 1924, and Vol. XII., No. 59, 1926.

vibrations in a fuel main. These have formed the basis of many experiments and research, but with the type of engine with which the paper is mainly concerned they are relatively unimportant because little difficulty arises from them; we found, I think in 1922, that the re-opening of the spray valve did not take place. With the open nozzle, however, there may be some doubt. The open nozzle is really the old type of nozzle used with the hot-bulb engine going back to Akroyd Stuart, but is now rarely used, and I do not think that it is to be recommended.

Vibrations in the fuel main with the slow-running engine may have a disadvantageous effect, when the necessity for a loaded spray-valve becomes greater; great tightness of this valve is necessary for high economy when working at the higher pressures. The subject is dealt with at some length in Dr. Sass' forthcoming book.

An interesting case in my own experience was where we had to delay the injection deliberately because of reversing, as we could not alter the position of the cam; so by providing a 30ft. fuel pipe we succeeded in getting the precisely right amount of lag required.

The question of the ignition lag is a much more interesting subject for high-speed engines; that there is a dwell in ignition has been appreciated a long time, as indicated in Fig. 18, which is taken from Riedler, 1916. As Dr. Ormandy has

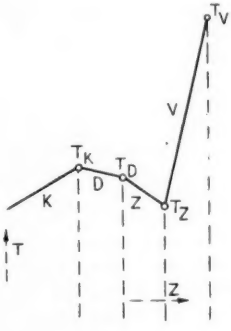

FIG. 18.

Gas oil (Riedler, 1916).

K = Compression. Z = Decomposition.
D = Vaporisation. V = Ignition and Combustion.

pointed out, ignition is much more difficult with oils derived from coal than with earth oils. In the earlier practice these oils were started on the way to combustion by a special pilot ignition oil or were mixed with oils that fired more readily.

The question of blending oils is of some importance, for it introduces the difficulty in the case of the high-speed engine that as soon as the practice of blending oils for use in such engines is extended the price will certainly go up, and, therefore, the advantage claimed for the use of a cheap oil for this type of engine will quickly disappear. Thus the use of an accelerator dope is hardly to be recommended as good practice.

In the comparative diagrams of ignition in the paper there are hardly enough figures to enable us to form a definite conclusion. The compression-pressure is given, but not drawn attention to in its effect; the point of injection is given, but the sizes of the cylinders are not given, nor is the turbulence, which is the most important factor. The authors would do a great service to designers

if they would extend their investigations and comparisons further to deal with this for all types with the rates of flow from 200ft. per sec. to 600ft. per sec. or whatever they may be. The experiments of the National Advisory Committee for Aeronautics give a figure for rate of pressure rise of 1,080,000lb. per sq. in. per sec. with an Akroyd Stuart type of combustion chamber with forced turbulence. In the Deutz the compression-pressure is low and the turbulence also. The Junkers engine with, say, a 15 : 1 compression ratio has a fairly high rate of rotary turbulence with a rapid rise in pressure. How much is due to the rate of air swirl and how much to the ratio of compression? The pressure in the pre-combustion chamber of the Körting is not given. In this type the turbulence is still higher.

I am impressed by the diagram showing maximum pressures of 980 to 1,110lb. (on Fig. 15 high turbulence). These are high figures for an engine in commercial use, and that is hardly the sort of diagram I should recommend. We want to see something below 800lb. if we are to get quieter running, and with this object it is hoped the authors will continue their work. The paper[16] by Le Mesurier and Stansfield can be studied with advantage in these comparisons.

Mr. J. Calderwood (representing the Junior Institution of Engineers): I do not agree with the authors' remarks as to the greater liability of the open nozzle to dribble as compared with the automatic fuel valve. I do not think that there is necessarily any greater risk of dribble with the open nozzle; it is, in fact, probably easier to design an open nozzle that is free from this trouble than to design an automatic valve which does not discharge fuel after the valve is closed. In the open nozzle, when used in conjunction with a short pipe, the closing of the pump delivery valve at the end of the injection periods draws the fuel back through the pipe, and, as a result, there is a considerable negative pressure wave which draws the fuel back from the nozzle to such an extent that the further expansion of the fuel as the pressure in the pipe drops to zero does not cause any more fuel to flow through the nozzle. With a valve there must always be a certain definite quantity of fuel trapped between the seating and the nozzle at the end of the injection period, and as the pressure in the cylinder drops, this must expand out through the nozzle.

In putting forward the above remarks I do not wish to suggest that the open nozzle is essentially the better system of the two, but there can be no doubt that very satisfactory results have been obtained with open nozzles. One advantage that I have noticed with the open nozzle is that it appears to give quieter running.

It is stated that the rate of pressure-rise after the initiation of combustion has a decided influence on the roughness or smoothness of running of the engine, but I do not agree with the view that the rate of pressure-rise in itself is the cause of rough running, although a high rate of pressure-rise may often be observed in cases where the engine is not running smoothly. If the rate of pressure rise were in any way directly responsible for the noise, then it would be the rate of pressure-rise on a time base that would have to be taken as the criterion. Actually, rough running occurs in both slow and high-speed engines, and in the slow-speed engine the rate of pressure-rise on a time base never approaches that which is quite normal in a high-speed engine, even when running very smoothly. Further, I have noticed in a good many cases that there is rough running with a comparatively small rise in pressure and a relatively moderate rate of pressure-rise. In one case the engine was of about 60 h.p. per cylinder, and certainly the crankshaft had nothing to do with the rough running, as normally the running was quite smooth and it was only under certain exceptional conditions that the engine was noisy.

[16] See *Proc. I.Pet.Tech.*, March, 1931.

I am inclined to think that the noise which is generally described as rough running is due to quite a different phenomenon, which has no direct connection with the rate of pressure-rise observed after the initiation of combustion. Generally, rough running is associated with a big time lag in conjunction with an injection system which allows a fairly considerable quantity of fuel to enter the cylinder during the time lag, and my own impression is that the noise is due to the building up in part of the cylinder during the time lag period of a mixture which, if it were in a petrol engine, would be liable to cause pinking. Immediately ignition starts, this body of mixture, which may be small or large, is burnt quickly under similar conditions to those which cause pinking in a petrol engine, *i.e.*, probably a localised pressure wave passes through the part of the cylinder filled with explosive mixture and causes a noise which externally sounds mechanical. These conditions may or may not cause a rapid rise in the indicator diagram. The pressure wave itself probably travels too rapidly to affect the indicator, and if the quantity of mixture which is in this condition is comparatively small, then the mean rise throughout the cylinder is neither very great nor very rapid. This phenomenon may occur with all types of compression-ignition engine both large and small, whether fitted with air injection or direct injection, and it is always more severe under cold conditions when the time lag is considerable. Rough running is, of course, more likely to be associated with a rapid rate of pressure-rise and a high maximum pressure in a small high-speed engine than in a large slow-speed engine, due to the fact that in the former the time lag is relatively much longer and a greater part of the cylinder is likely to be filled with combustible mixture under the conditions which will cause the pinking effect. Although this rough running is probably not of mechanical importance, as it does not impose any severe stresses on the working parts, it is, I think, one of the most important points to investigate, particularly in the case of small high-speed engines where quiet smooth running is very desirable.

Mr. W. A. Tookey: Though I am the official representative of the Institution of Automobile Engineers, my remarks are personal and not an official utterance. I think that my uppermost thought after hearing the paper must be that mechanical engineers who have evolved the compression-ignition engine have managed to solve a very complicated set of conditions in a very satisfactory manner without full knowledge of the many difficulties which the paper describes. Those of us who are concerned with the practical running of engines pay little attention as a rule to injection lag or ignition lag or anything of that kind. A definite size of cylinder has to be induced to produce a definite amount of power at a definite speed, while each unit of a multi-cylinder combination has to " pull " equally, and this frequently when the engine speed must be practically uniform, as in the generation of alternating-current electricity. We also have to ensure that our engines will continue to work reliably and economically at variable loads and speeds and, in fact, under operating conditions, which vary very considerably from the " static " conditions usually applying when laboratory experiments are in progress. We can tune up each cylinder by making the sprayer function a little earlier or a little later as compared with its fellows. In practical experimental work connected with new developments it is often the case that even with all the information which scientific research has placed at our disposal a difficulty persists which defies immediate solution. Then the practical engineer is very frequently most useful in suggesting the next step, and his suggestion is due to innate mechanical engineering ability, which, after all, is indispensable and must work hand in hand with scientific attainments.

Internal combustion engineers who have had the advantage of early gas engine experience know full well the very varying effects brought about by variation of cylinder-wall temperature, both as regards rapidity of ignition and completeness of combustion. They realise also the effects of heat retention in castings and the more or less gradual change in temperature of the containing walls, and

particularly at changes of section which cause differences in what might be called volumetric heat. I was glad to note that the authors have mentioned this in their paper, and I am in agreement with their conclusion that "each separate type of design is governed by laws which must be independently determined and not inferred from the designs." It must be realised that in practice the compression-ignition engine cannot be adjusted, as regards ignition timing, as simply as is permitted by the ordinary magneto used with gas or petrol engines. We have to arrange for the fuel to be injected at a more or less definite crank angle, and this for all loads from light to maximum, and under the ranges of temperature that are consequent upon the load changes and the corresponding rate of fuel admission as regulated by the governing mechanism. This, in fact, means that the actual setting of the injection has to be a compromise such that commercial guarantees as to rates of fuel consumption are fulfilled. It will be seen from this that the practical man has to deal with many matters of concern which the present paper does not envisage.

As regards combustion pressures, I am of the opinion that engineers developing mechanical-injection engines have to break down a considerable amount of prejudice which has resulted from statements by their confrères interested in the air-injection Diesel engine. It has been constantly repeated that combustion pressures in an airless-injection engine should not be greatly in excess of those noted in air-injection Diesels. I think this dictum must be disregarded. In the old days of the gas engine working with 40lb. per sq. in. compression-pressure the combustion pressures were usually of the order of 160lb., say four times as much. Later on gas engines with 100lb. compression-pressure produced combustion pressures of about 360lb. per sq. in., say 3.6 : 1. With the development of higher compression-pressures the ratio of ignition pressure has been found to be reduced, so that a mechanical-injection engine working at 420lb. compression-pressure to-day gives explosion pressures of the order of 630lb. per sq. in., or 1.5 times. Why should we be afraid of these higher ignition pressures which, without doubt, bring about higher thermal efficiency? They last for an extremely short period of the cycle and occur only when the minimum amount of wall area is exposed.

As long as the peak pressure is not reached while the connecting-rod is in a straight line with the cylinder axis, the stresses are not detrimental as affecting total engine weight. In the direction of higher combustion pressures ignition lag difficulties can be more readily dealt with, and while there may be a tendency to a slight combustion knock, this need not lead us into a search for a "dope," which, to my mind, is commercially indefensible if the high-speed compression-ignition engine is to be available for universal application.

Major G. P. Bulman (representing the Royal Aeronautical Society): I think that aeronautical development can claim in this matter of the high-speed solid-injection engine to have played some useful part. We have obviously the very great incentive that the heavy oil engine offers an escape from that, almost the one remaining, terror of the air, the crash fire; but, as in all other engineering problems, we have to compromise. We cannot pay too much for that freedom in military work, because weight means reduced performance; in civil work weight means reduced paying load, and, therefore, until the weight of the compression-ignition engine can be reduced to within reasonable terms we cannot expect it to be universally employed.

During the last two or three weeks a Junkers heavy oil aircraft engine has completed a 50 hours type test at 720 h.p. for a total weight of only 1,800lb. at a fuel consumption of 0.37lb. per horse-power per hour and a lubricating oil consumption of 0.03lb. per horse-power per hour, or a total combined oil consumption of 0.4lb. That same engine has achieved an altitude of 20,000ft., which is rather remarkable for an engine depending on compression for its ignition. On the other hand we have heard great claims from America of the

Packard Diesel engine, and recently have had the opportunity of testing one of these engines in this country. Whereas an output of 234 h.p. is claimed, the best we have been able to get is 210 h.p. at 1,950 revs. per minute, which was associated with a fuel consumption of 0.67lb. per horse-power per hour, whereas the claimed consumption is of the order of 0.38lb. Actually, the minimum consumption so far obtained is of the order of 0.495lb., which was secured with a mean effective pressure of 60lb. per sq. in.—which is disappointing. We may, however, have been unlucky in the actual engine and may not have learned the art of running an engine which is used to American atmosphere. As our own standard of development, we regard as a minimum criterion a performance of 100lb. per sq. in. brake mean effective pressure, a fuel consumption of not more than 0.40lb. per horse-power per hour, associated with a maximum pressure of the order of not more than 800 to 850lb. per sq. in. and a piston speed of, say, 2,500ft. per minute. In seeking that efficiency, and it can be said that we are in near sight of it, we hope we can claim that we are doing something to help the whole advance of the country in compression-ignition engine development.

Mr. L. J. Le Mesurier (representing the Institution of Petroleum Technologists): I agree entirely with the authors' remarks on the extreme importance of precision in manufacture, and consider that it is due largely to improvements in material and workmanship that the high-speed airless-injection engine has arrived at its present satisfactory state of development. Fuel pumps and injector valves can now be produced which give efficient and consistent performance over long periods. Pump leakages are found to vary inversely with the kinematic viscosity of the fuel, and it is therefore necessary, before accepting the results of the tests as given in Fig. 1, to know that each test was carried out with the same fuel and under the same conditions of temperature. It would be quite possible, for instance, to test a pump after service corresponding to 80,000 miles and to find less apparent leakage than when the pump was new, due to the use of a fuel of slightly higher viscosity in the second test or to a slight decrease in the temperature at which the test was conducted.

I think that the point that the authors make that the volume of pumps, passages, etc., should be made as small as possible should not be overstressed, because, provided the volume is kept within reasonable limits, it is unnecessary to make special and possibly awkward mechanical arrangements with the particular object of bringing the pumps close to the cylinder heads. For instance, in the case of moderately slow-speed marine engines there appears to be no objection whatsoever to placing the pumps conveniently on the bottom platform and connecting them by quite long pipe lines to the injector nozzles, of either closed or open types. In high-speed multi-cylinder engines the pumps may be conveniently grouped together in the position normally occupied by water pumps or magnetos in the ordinary petrol engine. The pipe lines led to the various injector nozzles will be found sufficiently small in volume for all practical purposes. If necessary, the volume of each pipe line may be equalised by varying the bores to suit the different lengths of pipe. In Fig. 5 there is nothing to indicate that any appreciable difference in performance is likely to result from the adoption of either pipe length. In both cases the period of opening of the injection valve appears substantially the same, and the difference in injection lag, of course, may be quite easily adjusted by suitably altering the static timing of the pump.

The curves in Fig. 11 showing injection lag with and without air swirl are not very helpful in making a study of combustion under engine conditions. At first glance these curves convey the impression that ignition lag increases with air swirl, and also that ignition lags are comparatively large and may amount to as much as 0.8 of a second. Actually, the ignition lags we are concerned with in high-speed engines are of a very much smaller order, and fall well below the point at which the two curves, A and B, cross. The significance of this diagram applied to engine conditions therefore lies only in the portion of the curves below

the crossing point, which shows that time lag decreases with air swirl. In the Deutz engine, running at 300 revs. per minute, the ignition lag, according to Fig. 13, appears to be about 0.017 of a second with air temperature of 300°C. and a pressure of 150lb. per sq. in. at the moment of injection. In the Junkers and Körting engines the ignition lags are 0.0066 and 0.0050 of a second respectively, indicating conditions very different from those under which the curves in Fig. 11 were obtained.

At the conclusion of the paper the authors suggest various matters which require investigation. Several of the points they mention have been covered in experiments recently carried out and described in a paper on " Fuel Testing in High and Low-Speed Engines " by Mr. Stansfield and myself.[17] With regard to ignition lag, we found from tests carried out on a Junkers high-speed engine and a Robey cold-start horizontal engine, the former with an open nozzle and the latter with a spring-loaded valve, that ignition lag is independent of fuel injection. For instance, the use of different nozzles in either engine showed that the size or shape of spray or velocity of injection did not affect the lag between injection and commencement of pressure-rise. Ignition lag was found to vary enormously from one engine to another, as is also shown by Fig. 13. Similar variations were observed between the Robey slow-speed engine and the Junkers and McLaren-Benz high-speed engines, which pointed to the definite conclusion that turbulence is the factor which chiefly affects the time lag with a given fuel. This point received further confirmation by observations that ignition lag decreases with increase in engine speed. It was found that, generally, delay angles on a given engine remain more or less constant, with the result that delay times or ignition lags vary approximately inversely with the speed.

With regard to fuel, an examination of engine behaviour, using fourteen different fuels in four different engines, showed that the *difference* between the ignition delay angle for one fuel and another is the same for any engine, although the differences tend to increase with very high turbulence. The approximate constancy of difference in delay angles is confirmed in rather a striking manner by Fig. 15, showing the effect of ethyl nitrate on Asiatic fuel in an A.E.C. engine running at 1,000 revs. per minute. An addition of 5 per cent. reduced the delay angle by 3 degrees. An addition of the same dope to tar oil in the Robey engine running at only 275 revs. per minute reduced the delay angle by exactly the same amount, and 10 per cent. had just double the effect.

An increase of delay angle was found almost invariably to lead to increase of combustion shock, and fuels may be roughly classified as regards their shock propensities by comparing the petrols produced from the crudes. It is found that crudes giving the most anti-knock petrols give the roughest running Diesel fuels, while those giving comparatively low anti-knock spirit give very smooth running Diesel fuels. In addition to an examination of ignition lag, it was also found equally important to examine the type of pressure-rise after the point of breakaway occurs. A number of typical diagrams showing the nature of this curve with different fuels is given in our paper.

It would appear that the results of experiments so far made indicate that it is impossible to correlate analyses of fuels with engine behaviour, and that an engine test will be the final arbiter in the case of Diesel fuels, just as it is now in the case of fuels for petrol engines.

Mr. R. Cook (representing the Institute of Fuel) : I will confine my remarks to the influence of turbulence upon smoothness of running. The authors state that, to avoid rough running, the slope of the line C—D in Fig. 8 must not be too steep. I cannot agree with that, because Ricardo has shown that in a petrol engine roughness is due, not to the absolute rate of pressure-rise, as shown by the line C—D, but to the sudden application of pressure at the point C. Thus, if the pressure be applied gradually at first, a very high rate of pressure-

[17] *Loc. cit.*

rise may be employed subsequently without any trace of roughness. Exactly the same thing applies to an oil engine, and I would suggest that this point be borne in mind when the form of the ideal indicator diagram is being considered.

The point is shown very clearly in Fig. 19. These diagrams were taken, by means of a Farnboro' indicator, from a petrol engine running at about four-fifths full load. The full line may be taken as a typical indicator diagram when a definite uni-directional swirl was given to the air; the dotted line shows the diagram obtained when the turbulence was of an indiscriminate nature. It will be seen that, with uni-directional swirl, the transition between compression and pressure-rise, as shown at X, is very abrupt. Under these conditions the running of the engine was very harsh. On the other hand the dotted line shows that, with indiscriminate turbulence, the *initial* rate of pressure-rise was lower, with the result that the compression line merges evenly and gradually into the firing line,

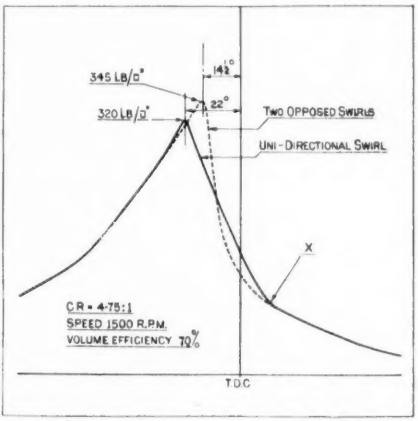

FIG. 19.

and smooth running was obtained in spite of the fact that the subsequent maximum pressure and rate of pressure-rise were greater than with uni-directional swirl.

In studying Figs. 13 (a) and 13 (b) I was greatly impressed by certain points of resemblance of Fig. 19. Thus the Deutz engine, in which no definite movement is given to the air charge, and in which, therefore, turbulence is probably of an indiscriminate nature, gives a diagram showing a gradual transition between compression and pressure-rise, whilst in the Junkers engine, in which there is a definite uni-directional swirl of the air, there is a fairly abrupt pressure-rise. It would seem that an abrupt pressure-rise is associated with, or is characteristic of, high-speed swirl of the air in high-speed oil and petrol engines.

Another point which I think should be borne in mind when considering the influence of turbulence upon combustion is that swirling turbulence leads to an increased rate of heat trasfer to the cooling water. This may have an appreciable effect on the nature of combustion. For example, in the case of the petrol engine referred to the heat-loss to the cylinder head cooling water is 25 per cent. greater with uni-directional swirl, and this probably accounts for the lower maximum pressure obtained.

Mr. A. L. BIRD (Cambridge): The point I should like to discuss is that of ignition lag. The authors give a diagram illustrating some work which was done at Cambridge, and state that the values of ignition lag are much too high to be correlated with those observed in actual engines. That is so, of course, at first sight. We were very puzzled by that lag of some 0.02 of a second, and we

elaborated methods of measuring it, but still we could not cut it down to less than, say, 0.016, making allowance for all the possibilities. Then we had in mind the idea of turbulence, in continuing the experiments, and we tried fans. Neumann's fan, judging from his illustration, was a fan at the end of the vessel remote from the injection end, and, incidentally, I should like to point out that in Neumann's diagram, Fig. 11, the ignition lag goes down to zero. I cannot quite understand that. We extended our fan in an annular fashion so that we could inject into a sort of cage. There is no doubt about the efficacy of these fans, because they were capable of putting out the ignition entirely. But the point is that with these fans we were again unable to cut down the ignition lag, according to our measurements, and, incidentally, this extinction of the flame rather confirms Dr. Ormandy's point that in this region it is just as well not to disturb the process, whatever that process may be. However, we were still puzzled by this lag, and in a later vessel, in which the diameter was smaller, we were able to get nearer engine conditions in the matter of excess air ratio. In the earlier vessel the excess air ratio was large, perhaps 10 : 1 or thereabouts; but in the smaller vessel a moving piston was fitted, and by placing that in different positions we were able to get down to excess air ratios of 2 : 1 or 3 : 1, as in an engine. That appeared to be the explanation of this large lag; as the excess air ratio was decreased from 10 : 1, by the time we had reduced the value to 4 : 1 we began to notice a very substantial change in regard to the ignition lag, and eventually, at an excess air ratio of about 3 : 1 and at densities and temperatures similar to those obtaining in an engine, we got ignition lag of about 0.004 of a second without turbulence. So that it appears to me that the authors' implication that turbulence is the factor which affects this ignition lag is only a partial explanation, if a true one, and that, after all, there is a much more sensitive process going on, and that during this preparation for ignition we have to be very careful what we do. After all, if relative velocity between the oil drops and the air is the aim, there would appear to be ample motion provided by the velocity of the oil drop itself, initially some 500ft. per second and dropping to 50 ft. per second at ignition, an average rather higher than normal turbulence. Turbulence will, of course, greatly affect the speed of burning after ignition has started. In the later vessel we had turbulence, in fact, of another kind. With the moving piston it was possible to force jets of hot air in different directions across the jet, and in that case we were able to reach a velocity of 120ft. per second. At that speed a jet of air is capable of extinguishing the flame from quite a large nozzle—0.015in. In the earlier vessel, using fan tip speeds of 40ft. per second, the flame from a small nozzle only 0.005in. could be put out. At lower speeds the rate of burning was increased several times as compared with still air.

There is one secondary point I should like to mention. The authors state that only five years ago the view was commonly held that the *indicated* thermal efficiency of the airless-injection engine would never approach that of the air-injection engine. Presumably that was because of the difficulty of mixing the oil and the air. Of course, we know that it has, perhaps, in some cases reached that efficiency, though not altogether, I think, because of improved injection, but rather because of the change of cycle. As we see from some of the figures, we get pressures of 1,000lbs. per sq. in.; in fact, it has been implied in the whole of the discussion that we are aiming at constant-volume combustion, which, I think, accounts for that improved efficiency, because it is difficult to understand how we can get the same effect from airless injection as from air injection, for with air injection there is four times as much energy available for mixing the oil and the air.

Mr. J. F. Alcock (Messrs. Ricardo & Co.): Is it safe to assume, as the authors have done, that changes in the cross-section of the fuel line do not affect the process by which the pressure is built up? In the simple case cited by the authors, where the plunger attains almost instantly a steady velocity and where

the pipe diameter is uniform throughout, we get a wave front moving along the pipe with the speed of sound. Behind the wave front there is a pressure such that the plunger displacement during any moment of time just equals the compression of the oil traversed by the wave front during that period. The oil already compressed suffers, therefore, no volume change and, consequently, no pressure change. Now suppose the wave reaches a constriction where the pipe area is halved. The wave now traverses only half the volume of oil in a given time, and the compression of this oil equals only half the plunger displacement. The other half must be expended in increasing the pressure behind the original wave front, presumably through a process of partial reflection similar to that occurring at the fuel jet. The effect of this would be, therefore, to smooth out the pressure steps shown in Fig. 4 with a series of smaller steps. In the average injection system there are several changes of section, and the total smoothing effect must, therefore, be very considerable.

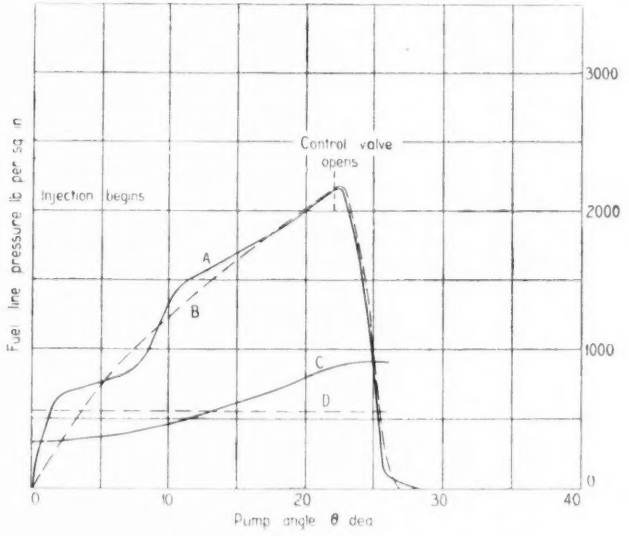

FIG. 20.

Ricardo pump, fuel pump diagram, 1,200 *revs. per minute.*

Full curve A =Actual fuel pressure diagram.
Dotted curve B=Calculated fuel pressure diagram from formulæ.
Full curve C =Actual cylinder pressure.
Dotted curve D=Mean cylinder pressure (assumed constant for calculation).

In most of the fuel line indicator diagrams I have seen there are either no waves at all or very slight ones rapidly damped. This seems to confirm the existence of some such smoothing effect. In a few cases violent waves occur and may cause the pump to four-stroke at certain speeds. A remedy is to fit an unloaded non-return valve near the pump end of the line, which damps the reflected waves. A similar device is used on the Constantinesco machine-gun synchronising gear for aircraft. Fig. 20, taken from an open-nozzle fuel line at 1,200 revs. per minute, shows well-marked waves, but the frequency of these is only one-third of that given by a simple sound-velocity calculation.

In Fig. 21 is shown a diagram of a type given fairly often by port-controlled pumps at high speeds. The initial " wave " is large and so rapid that the rising

and falling lines are indistinguishable, yet there are no further waves. Waves of this kind do not appear to affect the engine performance, but it would be of interest to know whether the authors have found any such effect and whether they have discovered its cause.

Dr. Ormandy mentioned a curious effect found in his " bomb " tests, where a certain amount of reaction occurred causing a rise in temperature, but without proceeding to complete combustion. A similar effect was observed in Tizard's experiments on ignition of homogeneous fuel-air mixtures by sudden compression. A diagram illustrating this is given in Fig. 7 of his paper on " Detonation in Internal Combustion Engines."[18]

Mr. Chorlton and Mr. Calderwood have discussed the relative virtues of the open type and the closed type of nozzle. Our general experience has been that the performance of the engine with either type is practically identical. There is a very slight dribble with the open type nozzle, but, as a rule, it occurs over only two degrees at the most, and appears to be quite unimportant as regards the thermal efficiency of the engine. It has one disadvantage, however, in certain classes of engine, that craters of carbon may be formed around the actual nozzle. This appears to occur mainly in engines in which there is not much turbulence. If there is a rapid flow of air past the nozzle these craters do not occur.

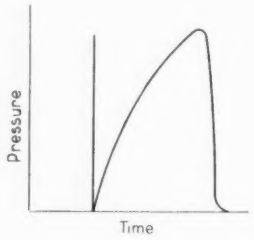

FIG. 21.

Mr. Bird's discovery that the ignition lag is considerably influenced by the air/fuel ratio helps to explain the fact often observed, that a Diesel engine is roughest at about one-half full load, and that the running becomes smoother at higher loads.

Mr. R. E. STRUB: I should like to try to correlate the points of view which have been expressed in the discussion by Mr. Tookey and those expressed by the authors, for they are somewhat in opposition. As a designer, I should like to testify to the great value of the results of trials given by the authors, even if they have been obtained in the stable conditions existing in a University laboratory. A designer to-day is bound to consider such problems as the lag of ignition and the ensuing questions arising out of the compressibility of fuel. It is quite true that it can be left to some extent to the engineer in the test bay to find out how to obtain the best results under all practical conditions—that is, different conditions of load, fuels and designs—but in the value of data such as given in the paper under discussion and elsewhere lies the possibility of shortening the time necessitated for development of a new type of engine. A proper application of the laboratory results of, for instance, the compressibility of fuels, might well shorten the costly path of trial and error which induces so many manufacturers in this country to buy licences abroad.

In Fig. 2 in the paper we have curves showing the compressibility of fuel oil, and in Fig. 3 there are curves showing the effect of temperature on compressibility. This effect of temperature on compressibility has worried us a

[18] See *Proc. N.E. Coast I. of E. and S.*, 1921.

great deal, and I should like to ask the authors whether Fig. 3 is correct in so far as it seems to indicate that the compressibility decreases with increasing temperature, because in my experience the reverse seems to be the case. This is one of the problems which is not accessible to calculation, inasmuch as it is based solely on the physical properties of the different fuels, and, therefore, must be left to the laboratory. The compressibility of the fuel has a great practical effect. In order to visualise this we take a fuel pipe of, say, $\frac{1}{8}$in. diameter and 3ft. long, and if we compress the fuel to only 500lb. per sq. in.—which is only one-tenth or thereabouts of the pressure in the actual injection—we compress the volume by a drop of $\frac{1}{8}$in. cube. One way in which the University people can help us is by investigating still more this question of compressibility for different fuels and at different temperatures. The compressibility has its effect mainly on the different closing of the injection. If the total working volume of a fuel pump is, for instance, ten times the volume of the actual fuel injected per working stroke, and if we have a compressibility, as given in Fig. 2, up to about 2 per cent., the effect of the compressibility will be multiplied by 10, *i.e.*, it will be 20 per cent. Ten times the volume of the fuel injected is very little to have in the pressure or delivery side of a fuel system—the fuel pump has to be very close to the injection nozzle—and very few designs achieve it, and then this proportion is reached only at full load. At smaller loads the proportion would be much greater, maybe up to 1 : 50 and perhaps 1 : 100, with a corresponding multiplication of the percentage of compressibility. Therefore, to the designer, the practical value of such a research lies in the fact that it gives him an indication as to how far he can go—how much volume he can afford to give to the working volume in the fuel pump, in the pipe line and in the injector itself so as still to have the control of the various factors in hand which lead to what might be called a precision ignition under all practical conditions of service.

Mr. S. W. Nixon (The M.L. Magneto Syndicate): With regard to Fig. 1, can the authors give any further information as to the conditions under which these results were obtained? Was the pump delivering to an atomiser, as in the actual application, or working against some constant-load device?

Can the authors make any suggestions as to a suitable method of comparing pump performance? The conventional volumetric efficiency is of little use when applied to pumps with port control. During the early portion of the plunger movement pressure commences to accumulate before the suction port is sealed, and cut-off does not become effective until a definite interval after the controlling edges are "line and line;" this effect depends on plunger velocity and the dimensions and shape of the controlling edges. At present, for comparative tests, we measure the delivery with the pump working against known constant pressures, with a fixed control setting. These tests are important in determining the capacity of a pump for any particular application.

The authors rightly emphasise the importance of injection systems of minimum volumetric capacity, especially for small high-speed engines. I have met with pumps which would be unable to deliver at, say, 5,000lb. per sq. in., the plunger stroke being insufficient to do more than compress the fuel in the system.

Reliable information concerning the physical characteristics of fuels is certainly scarce. Values for compressibility vary considerably. The values shown in Fig. 2 correspond to what might be termed a coefficient of compressibility of 1/30,000 per atmosphere. In some experiments I carried out I obtained a value of 1/10,000 per atmosphere with Shell Mex 40-seconds fuel oil, which value is also given by J. E. Wild.[19] The results are compared in Fig. 22. It is true that compressibility varies very little with pressure, but it should be remembered that the reduction in volume may equal or exceed the volume of the injected charge in some injection systems; thus the plunger displacement to provide for this may exceed that actually required to inject the fuel. In systems where

[19] See *S.A.E. Journal*, May, 1930.

there is not mechanical control of the injection period, the effect of the compressibility coefficient is to lengthen unduly the injection period as the load and speed are increased.

In regard to the authors' remarks on the question of pressure waves in a delivery line, until recently my own opinion had been that with short pipe lines these could be ignored. In connection with the application of fuel-injection gear to particular engines, I have been studying the relative importance of various factors which might influence the variation in the rate of injection over the injection period, the particular system consisting of a port-controlled pump and a differential needle atomiser. The variation of pressure in the delivery line was obtained with a Farnboro type indicator and pressure-reduction device. The volume displaced by the plunger is considered to be absorbed in three directions: (1) Overcoming the effect of compressibility; (2) causing discharge from the

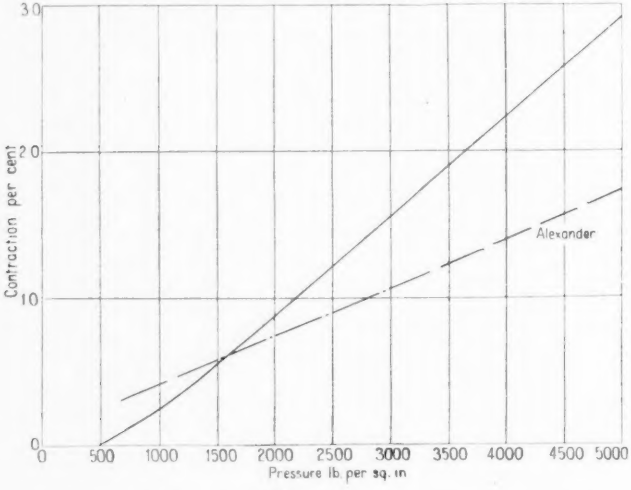

FIG. 22.

Compressibility coefficient = 1/10,000 per atm.
= 1/147,000 lb. per sq. in.
Corresponding values for Alexander's curve = 1/30,000 per atm.
= 1/442,000 lb. per sq. in.
"Shell Mex 40-sec." fuel oil.

atomiser; (3) leakage. Knowing the pressure variation and the discharge rates corresponding to various pressures, the curve of rate of injection can be plotted. Also, from the pressure curve, knowing the coefficient of compressibility and the volumetric capacity of the system, the volumetric rate necessary to give the pressure variation can be determined from point to point. The difference between the volumetric rate of displacement of the plunger and the sum of the above-mentioned items must be leakage. This method has been applied, but the values for leakage at certain points become negative; or, in other words, the sum of the rate of injection and volumetric rate to provide for compressibility is considerably greater than the rate of displacement of the plunger. This is considered to point to the conclusion that all the fuel is not compressed in the manner indicated by the pressure diagram. I should like the authors' opinion on this point. These various curves are shown in Fig. 23.

The open type atomiser is very simple, but, compared with the differential needle type, it suffers in several directions, especially when applied to an engine

suitable for vehicle work, *i.e.*, with a fairly considerable speed range. The orifice area of the open type is determined by compromising between satisfactory atomisation at idling speeds, and the very high pressures which must obtain under full load and speed conditions. With the differential needle type, injection cannot commence until the generated pressure exceeds that of the static load on the needle and a larger nozzle hole is permissible.

With regard to the work of A. L. Bird, I examined recently some curves showing engine consumption and coefficient of discharge on a common base. These varied considerably, but, in general, a high coefficient of discharge was accompanied by increased consumption. A high discharge coefficient indicates low

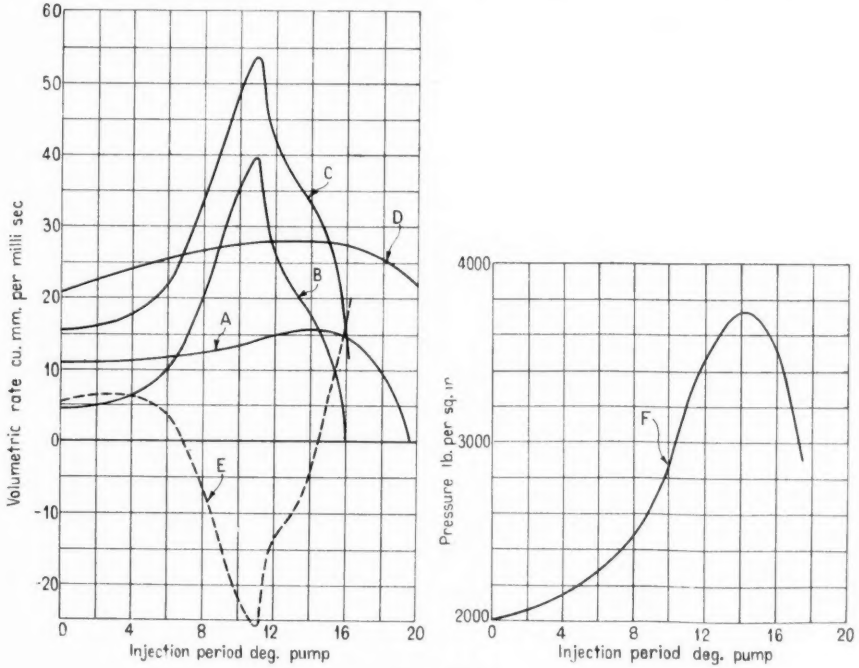

FIG. 23.

Curve A = Atomiser delivery rate.
,, B = Rate to provide for compressibility.
,, C = Sum of Curves A and B.
,, D = Plunger displacement rate.
,, E = Curve of D − (A + B).
,, F = Delivery line pressure.

energy loss in the transformation of pressure energy to kinetic energy. I suggest that the increased consumption is due to the unsatisfactory atomisation associated with low energy loss. Experiment with various differential type atomisers has shown that in good condition the discharge coefficient varies between 0.55 and 0.70.

Mr. C. B. DICKSEE : I should like to emphasise the importance of the influence of the delay period on the operation of the engine. The authors did not dwell upon the fact that during the delay period an appreciable amount of fuel is introduced. The longer the delay period the greater the quantity of the fuel

in the cylinder when combustion starts and the less control we have over what happens subsequently. If we are to smooth out the combustion of an engine, therefore, we want to secure the maximum amount of control over what happens when combustion starts. To do this we have two lines of attack; one is to decrease the delay period to the minimum, and the other to reduce to a minimum the amount of fuel admitted during that period. The ideal, of course, is to have the combustion starting the moment injection starts. Considerable improvement can be effected in the operation of the engine by changes in the fuel-pump cam and in the fuel. The effect of changes in the fuel is shown very clearly by Fig. 15 in the paper. That particular fuel is one which is thoroughly unsatisfactory in almost any kind of engine. The diagram in Fig. 15 is not advanced as an ideal, but it shows the tremendous influence which the delay period has. The effect of cutting it down from 13 degrees to 10 degrees was to produce a change which was such that, although the engine sounded more like a steam hammer when the un-doped fuel was used, the operation was relatively smooth when doped fuel was used.

Another point worth noting is that the delay period increases as the injection advance is increased; that is to say, when the fuel is injected into an atmosphere less dense and at lower temperature, the delay period is very distinctly increased. In fact, if we plot delay angles against injection angle, the increase is approximately in accordance with a straight-line law—at any rate, over the range I have investigated.

Wing Commander T. R. CAVE-BROWNE-CAVE: I quite agree that it is important to reduce the delay period to a minimum. It is not quite clear whether, under actual running conditions in an engine, it is the temperature and density of the air or the temperature that is mainly important. If it is the temperature which is important, preheating the air should be beneficial so long as the volume of air taken into the cylinder is not too much reduced thereby.

Experiments on these lines were started at the Royal Airship Works, but had to be stopped for other reasons. Only slight preheating to 107°F. was possible, but, as compared with an air temperature of 70°F., there was a decrease of maximum pressure of about 25lb. per sq. in. and no change in fuel economy at full power, but at half power an improvement of 0.363 to 0.358lb. per horse-power per hour.

The proposal requires much more thorough trial with much greater preheating, but it seems probable that considerably improved economy will be effected. If there is found to be any detriment at maximum power, preheating can temporarily be stopped. It appears to me better to extend the range of suitable fuels by preheating than by the use of dopes.

Dr. DAVIES, in replying on the discussion, said: If Dr. Ormandy's suggestion that the combustion processes should be further studied with the help of a variable-compression engine could be followed, it is certain that much light would be thrown on this all-important matter.

Mr. Chorlton expresses the view that vibrations in the fuel pipe only become important in slow-running engines; in so far as these vibrations determine the manner in which the pressure at the fuel valve is built up, so do they affect the process of injection. Although high-speed engines usually have shorter fuel pipes, due to the higher speeds, the actual injection lag and the rate of building up pressure, when *measured on crank angle*, will be affected, roughly, to the same extent on all engines. It is true that, with the present relative lack of control over the injection process, the effects have not been fully appreciated, but for future progress a better understanding is essential.

We would agree that the use of accelerator dopes with fuel oils at present difficult to burn is bad practice, since it shows the limitations of our knowledge of design; on the other hand, until an engine is designed which will burn these

successfully, the use of dopes for widening the sources from which fuels may be derived is not to be condemned.

Mr. Chorlton complained of lack of information in the cases of Fig. 13. We submit that the sketches supplied on the diagrams give an indication of the turbulence in the first two cases, whilst the Körting engine is dealt with fairly fully in the paper. One point about putting in these three engines is this: So many people are inclined to think that the results from one particular engine are of general application to all engines, but a comparison of these three engines proves that it is very dangerous to generalise at this stage.

In Mr. Calderwood's criticism of our remarks concerning the relative merits of "open" and spring-loaded fuel nozzles he appears to have overlooked our reference earlier to the use of special pump delivery valves. With his views on rough running we are in general agreement, but, as is urged in the paper, rough running is to be eliminated by designing to reduce ignition lag.

Mr. Tookey rightly pointed out the value of the "innate mechanical engineering ability" which the practical man must exercise, but the other side of the question—the value of laboratory experiments—was emphasised later in the discussion by Mr. Strub. We are at one with Mr. Tookey in his opinion that, with small engines, the fear of high pressures is often exaggerated. In view, however, of the common use of ethyl petrol, we do not follow him when he urges that the use of dopes is commercially indefensible.

Mr. Le Mesurier expresses the opinion that the effect of pipe length upon injection is negligible. But in the two pipes of Fig. 5 there are marked differences in the manner in which the injection pressure is built up and also in the periods of injection, the respective injection processes naturally being affected to a corresponding degree. We agree, and have in fact stated it, that the curves of Fig. 11 do not refer to "engine conditions," but they do show that turbulence has an effect upon ignition lag.

The experiments described in the paper[20] to which Mr. Le Mesurier referred have added greatly to present knowledge of the behaviour of fuels in heavy oil engines, and corroborate many of the views we expressed. He and his collaborator, Mr. Stansfield, are to be congratulated on a most valuable piece of work.

Mr. Cook does not agree with our view that rough running is caused by a high rate of pressure-rise, and refers to results from tests on petrol engines. That his conclusions do not hold when applied to heavy oil engines is shown by Fig. 15. Incidentally, this is further shown by Fig. 16 of the paper by Le Mesurier and Stansfield just referred to.[20]

Mr. Bird's account of his later experiments on ignition lag was very welcome and is especially valuable since the conditions now approach those obtaining in an engine.

Mr. Alcock refers to the effect on the process by which pressure is built up in the fuel system of changes in the cross-section. We agree that the steps on the curves of Fig. 5 would be smoothed out if such changes were taken into account, but the general form would remain. Surely his Fig. 20 indicates clearly that this stepped form does persist with an actual pump even with changes of cross-section.

Mr. Strub asks concerning the effect of temperature upon compressibility. The results in Fig. 3 are in accord with his experience—the compressibility is the reciprocal of the bulk modulus. His later remarks further emphasise the need for more exact knowledge of the properties of fuel oils.

We regret not being able to give Mr. Nixon fuller particulars regarding the tests in Fig. 1. He suggests the possibility of standard tests for fuel pumps.

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[20] *Loc. cit.*

In view of the diversity of present design, a diversity which, for the future progress of heavy oil engines, must increase, we submit that it is yet too early to attempt to standardise tests.

Mr. Nixon's tests, shown in Fig. 22, on the compressibility of a fuel oil give further valuable data; they show how widely compressibility may differ with different fuels, and also point the need for an extended investigation of this matter.

The tests of which the results are given in Fig. 23 are most interesting, and we are asked concerning the apparently contradictory values obtained. It would appear that curve B depends upon the *varying slope* of curve F; now, while the general form of F may be reasonably accurate, the form of B is thus so sensitive to error in the slope of F that this might well account for the results. For instance, taking an extreme case, a steady rise of F, over the pressure range shown, from 0 to 14 degrees would lead, in spite of the relatively slight alteration of F, to a constant value of B, quite different from the curve shown. Incidentally, ought not B to pass through a zero value at 14 degrees, corresponding to the peak of F?

Mr. Dicksee supports our view that a better control over the ignition lag is one of the important lines of advance with heavy oil engines. His results with varying point of injection corroborate the conclusions drawn from Fig. 13.

We agree with Commander Cave-Browne-Cave that the data available to-day concerning the effects of air temperature and density upon ignition lag under actual running conditions in an engine are quite insufficient. Pre-heating the air is a matter for compromise with a particular engine running under definite conditions, since, apart from the effect on volumetric efficiency, both ignition lag and rate of pressure-rise may be separately influenced.

COMMUNICATIONS

Col. A. E. DAVIDSON wrote: Two points which have not been dealt with are the quantity of excess oxygen that exists even in those engines which give the best performance, and ease of starting.

Dealing with the former, Ricardo does not apparently claim to be able to obtain a better result with clean exhaust than approximately 20 per cent. of excess oxygen. Certain engine makers claim to obtain a figure of about half this quantity, but only by the use of very fine jets. It remains to be seen whether these fine jets will be reliable in practice. It is not an easy matter to manufacture them correctly, and the fuel must be strained very carefully to ensure the removal of even the finest particles before it reaches them. This subject is of great importance from the military point of view where it is essential that the maximum output should be obtained from an engine of given dimensions. Where such an engine has to be placed beneath armour, not only has the extra weight of the engine to be taken into account, but also that of the armour, which may be a larger factor than the saving on the engine itself.

The starting of high-speed compression-ignition engines presents far greater difficulties than is the case with petrol engines. In general, the mass which has to be accelerated is considerably increased, the compression to be overcome is considerably higher, and the rate of revolutions which must be reached before firing commences is also greater. For military requirements in particular and for most road users it is very desirable, if not essential, to have electric starting, and this in view of the added difficulties mentioned above is not easy unless batteries of undue weight and size are employed.

Engines with ante-chambers are, generally speaking, harder to start because of the additional surface of cold metal. Those which have large jets, which are to be preferred on the score of easy manufacture and reliability, are also more difficult to start. In this respect the very fine jets referred to above show up to

considerable advantage. In certain engines the compression is raised at the moment of starting by various devices so as to increase the temperature of the compressed air, and by this means ensure more satisfactory firing, but these arrangements tend to increase the difficulty of turning the engine over against the compression. Dopes have also been employed for assisting in starting, but their use is undesirable, as one of the advantages of the heavy oil engine is that no highly inflammable fuel is carried on the vehicle. It would appear, therefore, as though research would be well repaid as to means of enabling high-speed compression-ignition engines to be started readily without the necessity of turning the engine over at a relatively high speed of rotation.

Mr. G. B. Fox wrote: On the subject of ignition lag the diagrams shown in Fig. 24, taken from heavy oil engines with the Dobbie McInnes Indicator,

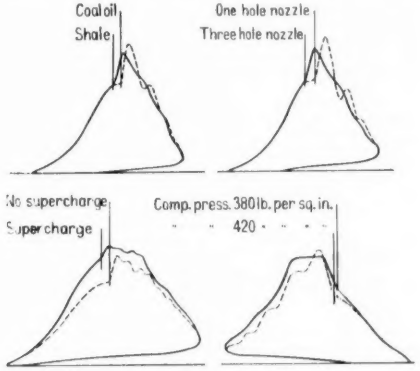

FIG. 24.

may be of interest. The problem is mainly one of raising the temperature of the fuel to its ignition point as quickly as possible, and this is again dependent upon the distribution of the fuel in the hot air with which it has to be associated. In the heavy high-speed oil engine the ignition lag is influenced by:—

1. The type of fuel used.
2. The different treatment in the manner of spraying the same fuel.
3. The degree of supercharge (if any).
4. The compression ratio.

In each pair of diagrams in Fig. 24 the timing is unchanged. No. 1 shows the difference of lag between two fuels. No. 2 shows the change of lag using different nozzles. No. 3 shows the effect of supercharge. No. 4 shows a slight difference in lag due to a change of 40lb. per sq. in. in compression.

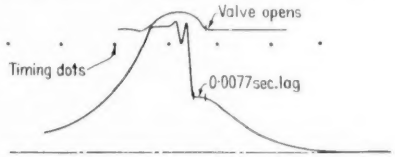

FIG. 25.

Starting diagram showing lag between ignition and injection.

I should like to refer Dr. Davies to Fig. 25, which is a diagram given in a paper entitled " Indicating Oil Engines " read before the Diesel Engine Users'

Association in 1929. The diagram was taken on a special indicator having a drum 4½in. diameter and driven by high-speed clockwork. The indicator had four pencils, the first merely drawing the atmospheric line, the second indicating pressure-rise, the third marking the paper with dots, the intervals between which represent a certain fraction of a second, and the fourth draws the valve-lift diagram.

In a diagram taken by this instrument the lag may be seen in relation to the actual valve lift. Injection begins when the valve lifts, not necessarily when the roller clearance is just taken up; since we are speaking in terms of fractions of a second, these two points are not identical. Injection was effected by five holes, approximately 0.017in. diameter, the fuel pressure being 4,000lb. per sq. in. Had the holes been slightly smaller and more in number the lag would have been reduced, the rise of pressure would have been more gradual, the maximum pressure less, and the exhaust, when on load, black. In this type of engine a rapid rise of pressure is essential to good combustion; this rapid rise is produced by conditions which give lag between injection and ignition.

In reply to the written communications, Dr. DAVIES wrote: Col. Davidson mentions two important points in which there remains a need for improvement in heavy oil engines, namely, a reduction of the size and power/weight ratios, and easier starting.

As regards the former, a better understanding of the mixing and combustion processes should tend to reduce the proportion of excess air and to lead to higher brake mean pressures.

The question of starting is, to some extent, bound up with the flexibility of the fuel injection system; at present, injection is in its most unfavourable state at starting speeds. With the improvements to be reasonably expected in this connection, starting difficulties should be reduced.

Mr. Fox's contribution gives further valuable experimental data concerning ignition lag. He states that, with the engine described in the paper before the Diesel Engine Users' Association, a rapid rise of pressure is essential to good combustion, and assumes that good running conditions cannot be associated, in this case, with a short ignition lag. It would appear, however, that with the smaller size of holes the black exhaust was due to unsatisfactory mixing caused, for example, by insufficient penetration or faulty distribution. If the form of the combustion chamber could have been altered to suit the change in the jet, it is probable that, since everything else was improved, the running would have been better from every point of view.

REVIEWS

Stress Diagrams and Drawing Office Practice

E. N. Digweed. Williams & Norgate. 8/6.

This is a rather curious book. The author starts with a chapter on drawing office practice, takes a plunge into the intricacies of stress diagrams, then, rather surprisingly, proceeds to derive the formula for a catenary curve with the aid of the calculus, then returns to the stress diagrams and finishes with a few pages on simple graphical balancing.

He commences with a detailed description of a method of sharpening a pencil, illustrated by three diagrams adorned with a dozen or so reference letters, and continues with half a page on how to pin paper to a drawing board. Having illustrated and described the use of ordinary drawing instruments he then proceeds to a sketchy account of certain aspects of drawing office practice. While there is nothing to object to particularly in this account, the reader should be warned that many heads of drawing offices have very different views from Mr. Digweed on this matter, and that drawing office practice is very far from being standardised. Had this chapter been more complete and less dogmatic the book would have gained in value.

With regard to the section on stress diagrams, Mr. Digweed does not always define his problems with the necessary accuracy. For instance, when he talks of fastening a string to a point on a sphere which rests against a wall, it should not be necessary to guess which would be the most likely point. One also objects to being told that one may treat a frame with rigid joints on the assumption that it is pin-jointed without appreciable error. The error may be very appreciable; fortunately it is usually on the right side.

Again, the author gives us a frame which is admittedly not rigid and informs us that it can be made rigid by adding one bar and perfectly rigid by adding two others. Actually, after adding the one bar the frame is certainly not rigid, and after adding the two others is equally certainly redundant if the bars are capable of taking both tension and compression. Loose language of this type is unpardonable in a book of this description.

Although the author devotes much space to discussing trusses of various types, no hint is given that such structures are self-stressed by their own weight, and he does not even refer to this matter when discussing the chains of a suspension bridge.

If the subject had been properly dealt with this would have been a useful work. Unfortunately it contains too many inexactitudes and ambiguities to be recommended to students, for whom, presumably, it was written.

Barnard on Learning to Fly

Captain C. D. Barnard. Sampson Low. 15/-.

Captain Barnard is beyond doubt one of the best British pilots, and this book of his on learning to fly is a pleasure to read as far as the chapters on practical flying are concerned. His constant insistence on the dangers of stalling is of the utmost importance and may save lives, and every embryo pilot and many experienced ones would fly better and more safely after having digested and applied Captain Barnard's general advice on piloting.

It is most interesting to read the author's support of the practice of side-slipping as a method of losing height when coming in to land. Although there is some difference of opinion on this matter among pilots there is no doubt that Capt. Barnard's views on the question are sound, and his point that one can see much better out of an aeroplane when it is side-slipping than when it is spiralling will become more and more important as aircraft become more popular and aerodromes more crowded. One would have liked to have seen a few general comments on types of light aircraft for the guidance of the novice who may be contemplating the purchase of a machine. For instance, his views on the comparative visibility from different types would have been of much interest.

Captain Barnard's notes on aerodynamical matters in the first chapter are more curious than correct, and the reader is advised not to take them too seriously. Also, the book is worthy of a better type of illustration. Incidentally, with reference to one of these, a ship does not always lie head to wind, as the currents in the water often deflect it considerably from this position.

But it is for the chapters on piloting that this book will be read, and it will repay the reading.